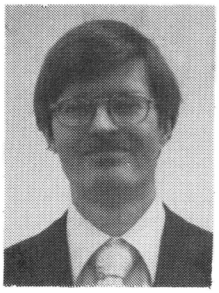

Editorial

H. J. Caulfield, Editor

On Sufficient Originality

Much confusion has arisen from the requirement that publications in *Optical Engineering* be "original." Coupled with my insistence that no paper is so original that it can stand without reference to prior work is the question: "How much originality is sufficient?" Surprisingly, few people ask. Virtually everyone "knows." Unfortunately, there is no unanimity. Stating my standards of sufficient originality as clearly as I can should help explain my publication decisions to irate, or at least annoyed, readers and referees.

By way of introduction, I must repeat my oft stated belief that a published paper should be primarily neither a goal nor an award. Its purpose should be to provide a tool for the thought and work of others. The principal criterion of a tool is usefulness. A hammer with feathers on the handle is an original concept, but it drives nails no better than an ordinary hammer. Its originality is clear, but its usefulness is not. I want to limit publications to useful new developments.

Likewise, I am very suspicious of "me too" papers that apply a known (but usually recently developed) concept to a problem only slightly different than that of previously published papers. A paper can escape the "me too" category by being original in the application as well as by being original in the method, but originality in at least one or the other is required.

Who sets the standards though? And what makes them so wise as to set the standards fairly? The answer is clear but the criteria are not. I set the standards with the often conflicting advice of skilled referees. I tend to weigh less heavily advice from referees who have "always known" what the writer has stated. Our referees are, after all, the best. What they have "always known" by years of experience or brilliant intuition may not be known to the vast majority of readers. Knowledge that does not appear in print anywhere is likely to be either trivial or new. Believing that I can detect triviality easier than I can detect originality, I am inclined to decide that nontrivial observations that do not appear in print elsewhere are "sufficiently original." Referees who argue against the originality of a manuscript can do so persuasively only by finding a suitable reference. This places a major burden on the referee, but that burden has really always been there.

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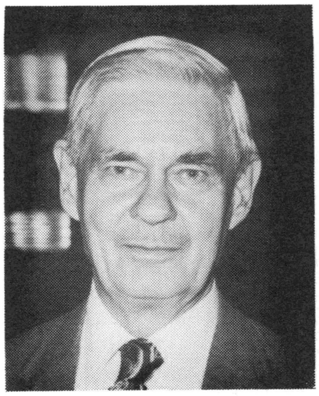
Dialogues in Optics

AN INTERVIEW WITH RUDOLF KINGSLAKE



Rudolf Kingslake's career as an educator and lens designer spans more than 50 years. He has taught courses in lens design and geometrical optics at the Institute of Optics of the University of Rochester since its founding in 1929 and also headed the lens design department at Eastman Kodak Company for more than three decades. Dr. Kingslake received his Bachelor's and Master's degrees from Imperial College and his Doctorate from London University. He has authored and edited several books and articles on lens design and has been the recipient of numerous awards and honors. Now retired, Dr. Kingslake teaches a summer school course at the Institute of Optics and recently has been writing and editing books on lens design and system layout and writing histories of optical companies.

The following interview took place on August 24, 1982, at SPIE's 26th Annual Technical Symposium in San Diego, California. Robert E. Fischer, SPIE's Vice President/President Elect for 1983, and Department Manager, Optics, Hughes Aircraft Co., conducted the interview.

Robert Fischer (BF): Good morning, Dr. Kingslake. I'd like to begin by asking about your first exposure to the field of optics.

Rudolf Kingslake (RK): My father was an enthusiastic amateur photographer, and I began to wonder about how the lenses on his cameras worked. He had a nice little book published by Beck, which showed sections of lenses, and I became curious about why it took six elements to make one kind of photographic lens whereas another type of lens only had four elements. So, when I heard that Imperial College had a department of optics where lens design was taught, I decided that was the obvious place for me to go. Imperial started the optics department in 1917 at the end of war; I went there in 1921, so the department of optics was still practically in its infancy. I was in the second regular, full-time undergraduate class, which lasted three years.

BF: Then you studied directly under Professor Conrady?

RK: Professor Conrady taught the lectures on lens design, L. C. Martin taught general optics, and B. K. Johnson did the laboratory work. In fact, we'd virtually live in the laboratory, leaving it only to attend a lecture and then returning to the lab. It was basically a lab course.

BF: Your education at Imperial College, then, was indeed quite practical, with background in the theory of lens design as well as a substantial amount of lab experience.

RK: Yes, and our experiments often lasted two or three weeks. When they were finished, we'd write them up. Martin used to insist that every lab report be ready to put in the journal—complete with illustrations, drawings, the whole works.

BF: Were some of your lab reports published?

RK: They never did get into the journal, but they had to be in a form such that they could have been published right away with properly finished drawings. Martin was terribly fussy about that. It was good for us because we learned about writing papers, even as undergraduates.

BF: You later married Professor Conrady's daughter?

RK: Yes. That was in 1929, before we came to the U.S.

BF: I'm wondering about the influence on your overall career of your marriage to the daughter of an optics professor.

RK: Hilda was in the optics department also. She was one of three students in the first regular undergraduate course; there were four in our year, and two in the following year. We all worked together and got to know each other very well. There were only one or two graduate students at that time; they came later.

BF: What about your degrees?

RK: I got a Bachelor's degree in 1924 and a Master's in 1926. In 1927 I left the university, got a couple of small jobs, then came over here in 1929. My D.Sc. degree from London University came much later, in 1950.

BF: Were these first jobs in England in optical design?

RK: One was for Grubb's, in Newcastle. There wasn't much for me to do there. My next job, which had nothing to do with optics, was for a telephone company. But I did learn some electronics, which was useful.

BF: Ultimately, you and your wife moved to the United States. Why did you leave England?

RK: Dr. Rhees, then President of the University of Rochester, came to England searching for faculty. It's all in the *History of the Institute of Optics,* which my wife wrote. Kodak and Bausch & Lomb were planning to help finance an Institute of Optics at the university. Dr. Rhees reckoned that there weren't any suitable faculty in this country; I don't know why. When he came to England recruiting faculty, he got me and also a man named Taylor from Cambridge. We were the first two faculty members at the Institute. A year later O'Brien, who was an American, joined us, and he was followed by Gustave Fassin from Belgium. It was quite a mixed-up blend of faculty.

BF: You started teaching at the University of Rochester in 1929?

RK: We had only optometry students at that time, about eight of them a year. After a couple of years, optics students began to appear. It was the time of the Great Depression, and why they kept the Institute running during the Depression I have no idea. Rhees must have had plenty of faith in it. That's all in the *History of the Institute.*

BF: After teaching at the university for over fifty years, how would you compare students in earlier years to today's students?

RK: Our early optics students were very good, and some have become quite famous. Taylor and I taught only classical optics, geometrical and physical, while O'Brien taught physiological optics. There wasn't any such thing as "modern optics," which started about 10 or 15 years ago, mostly as a result of the development of the laser. This discovery led to the study of quantum optics and coherence, with holograms, image processing, solid-state detectors, and many similar fields developing as a result.

BF: Do you think that students today derive a better understanding of the technology than they did in an earlier day, or the converse—do you see any difference?

RK: Oh, no. Optics, to my thinking, splits into two classes—what you might call classical optics and modern optics. Classical optics' students get bachelor's degrees and go into industry. They become lens designers, system designers, and instrument designers. Then there are the modern optics people, who usually come in from other universities with bachelor's degrees. They study for the Ph.D., and then they go on to get jobs in research labs. The two are really quite separate. Master's and bachelor's students are instrument types, and Ph.D.s are research types. We get both kinds of students at the University of Rochester.

BF: Do you think that in the field of lens design there are better lens designers today than in former years?

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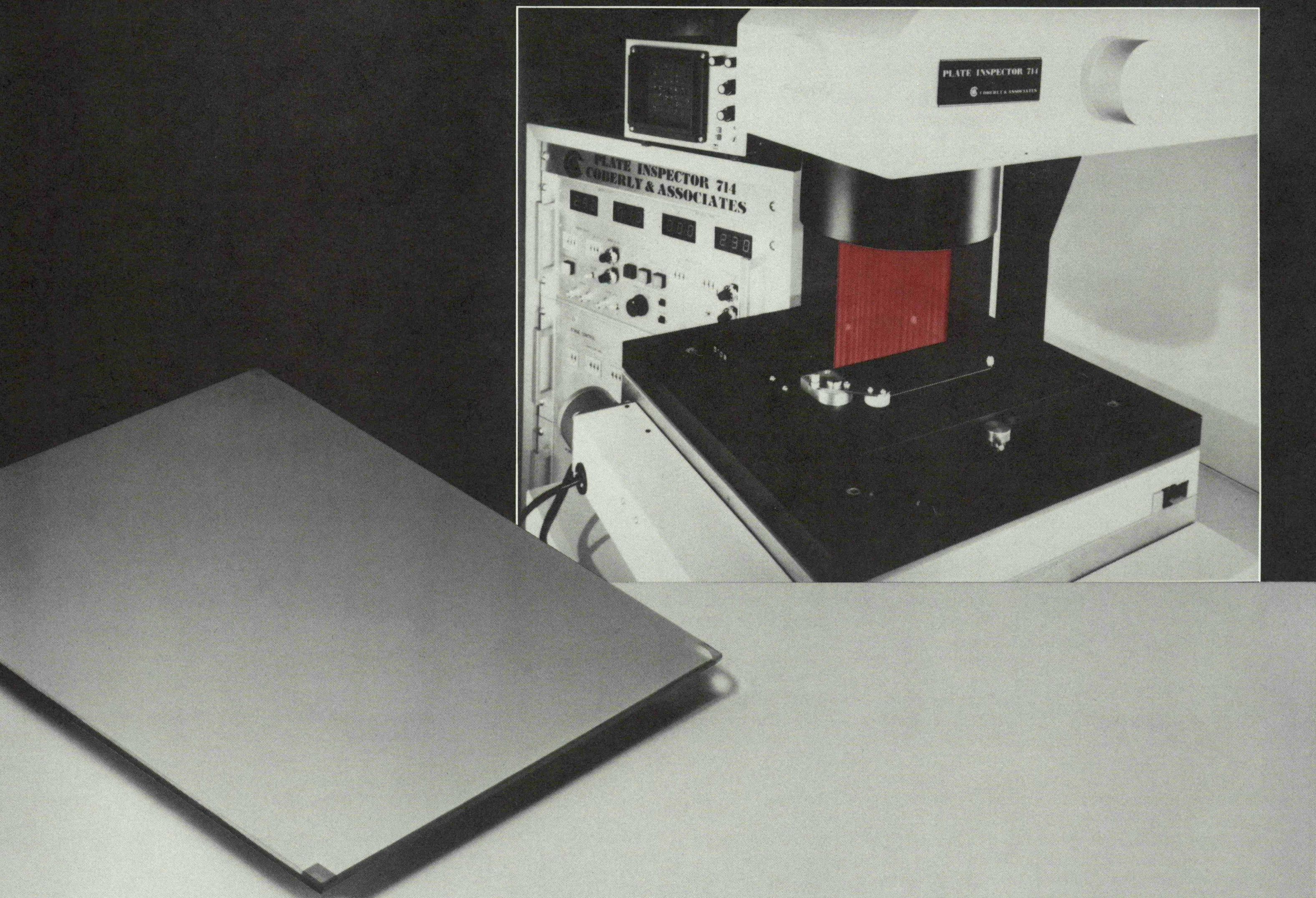

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RK: It's quite different today with the computer. The computer has changed everything. When I was at Kodak, if we wanted to hire a lens designer we'd ask, "Can you picture yourself punching the buttons on a desk calculator for thirty years?" Nowadays it isn't like that. You don't punch buttons on a calculator; you do it with a computer.

BF: Do you think today's designers have the same understanding of the problems of lens design since the advent of the computer?

RK: Probably not, but it isn't really necessary. In the old days, you had to know everything about your lenses because that was the only conceivable way you could operate. Life wouldn't be long enough if you had to research everything as you went along. So the old-time lens designers knew lenses like, say, you might know your child—you know all about it from beginning to end.

BF: Do you think that we derive better performing systems today?

RK: Oh, yes, much better—at least an order of magnitude better.

BF: Relative to the future of optical design technology, what is your opinion about the more powerful computers that are evolving, ultimately enabling the designer to reach a global minimum?

RK: We've seen no sign of it yet. Don Feder at Kodak and many other people are working on the problem without much success. A computer can only improve the design you give it, while a global minimum might be a long way off. To find it would require the design to become worse in order that it might eventually become better. A human designer can make a big step and then let the computer optimize it, but it is difficult to know how to recognize a global minimum when you have one.

BF: What you are saying, of course, is that there really is a need for the individual, the optical designer, in the process of lens design.

RK: At present, yes. It's conceivable that a really big computer could make all the big steps as well as the little steps. That's looking into the future.

BF: There was a paper presented at the 1980 International Lens Design Conference on the global minimum that was achieved with the design of a landscape lens and the ability to move that lens from one side of the stop to the other. Any extension of this to more complex systems simply did not work.

RK: I don't know, maybe it could. For example, suppose that in a Tessar lens someone thought of the bright idea of turning the rear doublet around so that the cemented interface would be concave to the stop. To do this, he would only have to interchange the two glass types, and the computer would do the rest.

BF: But, of course, the designer had the initial influence on the change.

RK: All he did was interchange the glass indices. He could have interchanged something else. To do that design by hand was a major operation. Kodak made Tessars both ways, and the ones with the surface concave to the stop seemed to be better on the whole. But it involved using very high index glass, which was then just becoming available.

BF: Speaking of glass, what do you foresee as the future of glass technology—do you envision any major advances in the industry over the next ten or twenty years or more?

RK: It is difficult to say. The Schott company, a pioneer in this field, is making some novel types of glass with serial numbers in the fifties which are useful for many purposes such as the reduction of secondary spectrum, but these glasses tend to be expensive and rather unstable, and are available in only small pieces.

BF: One new technology related to glass is the use of gradient index. Do you anticipate that as becoming a reality.

RK: It looks very promising, particularly as a way to replace aspheric surfaces. I don't think gradient indices will have a place in ordinary lenses, but where an aspheric is now being used, a gradient index glass could replace it. Duncan Moore is working on gradient index lenses at the University of Rochester. He is making the glass himself because he cannot get anyone else to make it. Unfortunately, every piece comes out different. To make a lens from this glass, he first makes the piece, then measures the index gradient, designs a lens around it, and makes the lens. That is all. The whole job is finished, and he has to start all over again to make the next sample.

BF: Aren't the Japanese doing substantial research relative to camera lenses using gradient index?

RK: It's quite possible. One area is in GRIN rods, and so far they've done wonders in that line.

BF: Aspherics, of course, use standard glasses. Do you foresee aspherics as becoming more commonly used?

RK: That seems to be happening. Canon claims to make a line of aspheric lenses. Kodak, of course, is using an aspheric in their Disc camera lens. They won't tell how they do it, although I have my ideas. Aspherics will do things that no other lens will do, but they're very difficult to manufacture.

BF: Speaking about Eastman Kodak--you began to work at Eastman Kodak in 1937. Why did you select Kodak?

RK: I didn't; they selected me. Dr. Mees, the director of research at Kodak, was looking for a lens designer to replace Mr. Frederick, who was way over retirement age. I'd been teaching at the university for seven years when Mees turned up one night at an evening lecture I gave, much to my astonishment because he didn't favor little people like me. Evidently, he was trying me out and invited me to join Kodak. How could I refuse?

BF: What would you consider to be your more significant accomplishments and tasks throughout your career at Kodak?

RK: Hiring people is one, I think. I hired Don Feder, who was a very great acquisition in the software area. Kodak was buying a big computer at the time. They bought an IBM 705 for business applications, and we thought this was the beginning of a computer system that Feder could work on. As it turned out, the 705 was a hopeless machine for computing although it was fine for business. For instance, it had a 200-bit word and other capabilities that were of no interest to us. However, they kept building better and faster machines, and eventually Feder found a machine that he could use.

BF: In terms of your efforts at Kodak relative to their optical systems and camera lenses, is there any one lens that was either the most difficult or challenging to design?

RK: No single lens stands out as most difficult or challenging. Of course, the war came along soon after I started there. Then we had to make everything. We made military instruments, range finders, telescopes, zoom telescopes for tanks, things that weren't photographic. We also made aerial camera lenses, a 36-inch, a 24-inch, a 12-inch, and the 7-inch f/2.5, which is quite famous. We had about twenty people working on lens designs at the time. New requests were always coming in from management or from the Army or from somewhere else. General Goddard would amble in and say, "Could you people make me a something or other?" and we'd answer, "We'll see what we can do." Fairchild took all our photographic output and put our lenses on their cameras, most of which went to the Air Force.

BF: That sounds like a rather challenging time of your career.

RK: It was a very challenging period because we had to do everything in a hurry. Things were wanted immediately.

BF: Do you think the technology took a major step forward during that period?

RK: I don't think so. What we were doing mainly involved hard work. We'd work Saturdays and nights punching buttons on desk calculators. We had no computers, nothing to help us. It was plain hard work.

BF: What is the most significant technology advancement over the years (it's a very broad question, I know) that you have seen?

RK: I think computers have been the major advance, but manufacturing methods have vastly improved also. At Kodak, Dr. McLeod and his group developed high speed polishing machines, which are used extensively, and Art Simmons built a number of automatic centering and edging machines. During the war he made several large pantographs for reticle engraving, and he also developed a new type of nodal-slide bench for lens testing.

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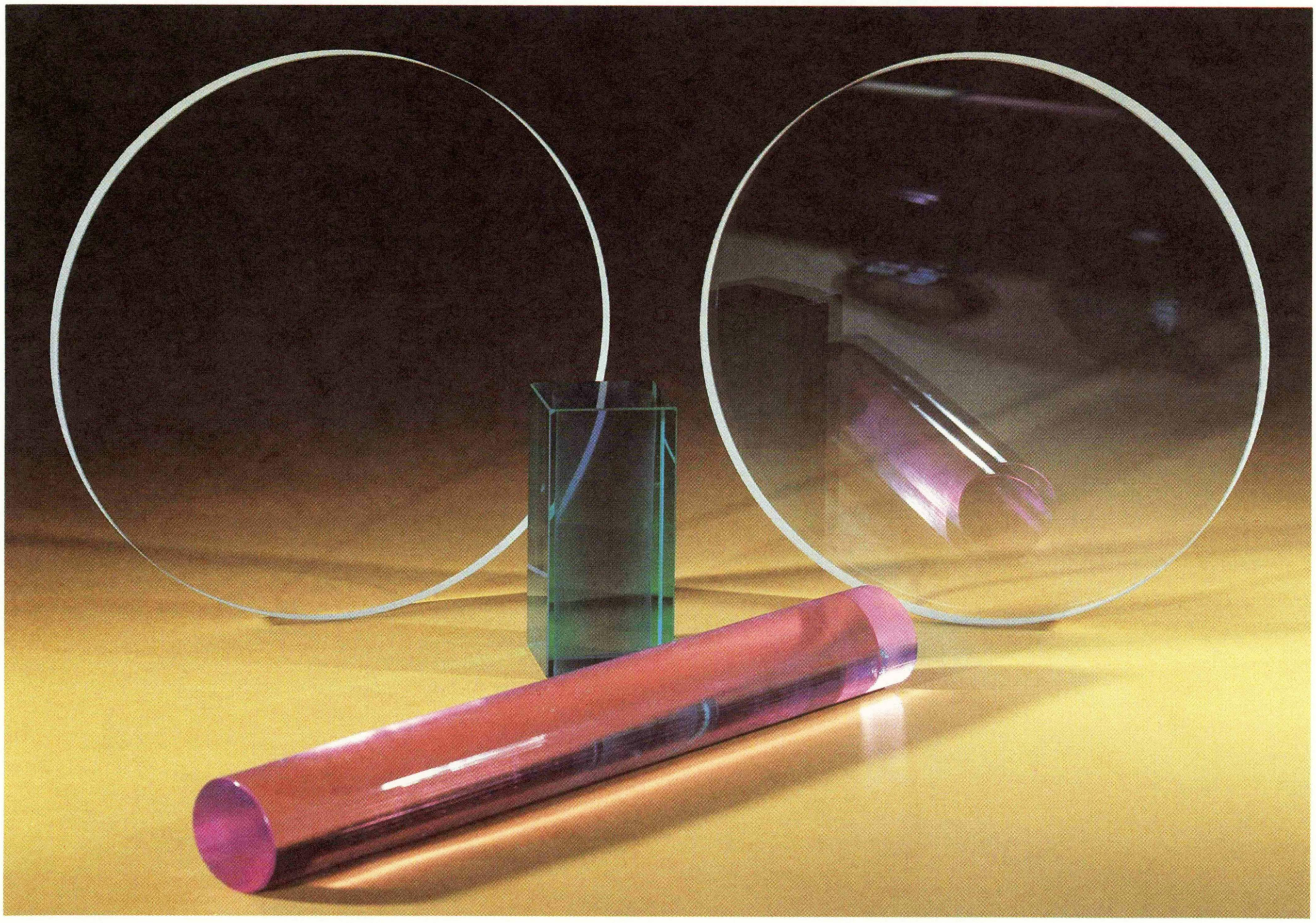

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BF: What do you feel will be the influence on optical systems, including amateur photography, of solid state imaging?

RK: I don't know much about solid state, but undoubtedly it is coming. Kodak, Xerox, and other companies both here and in Japan are working on electronic cameras, which for some purposes may replace silver halides as image detectors. This has all happened since my retirement fourteen years ago. I can picture a tiny Xerox machine that looks like a camera; no reason why not. Then there are things like CCDs, which have a huge future. I am sure they can be built into cameras of small size.

BF: Do you think that these technologies will put additional demands on the lens system?

RK: I don't think so, because the same lenses that are used for a camera could be used with a CCD.

BF: Do you envision any other technology developments that might impact the optical system?

RK: I have already mentioned new types of glass and gradient refractive indices. Mirrors offer some advantages, especially in large sizes. Otherwise, lenses still consist of a succession of crown and flint elements, as they always have.

BF: Of course, we have seen the development of systems such as the Polaroid SX-70 camera, which is rather unique in its design form and structure.

RK: The viewfinder in the SX-70 camera is most unusual and quite complicated, involving mirrors and a decentered Fresnel lens element. It was designed, I believe, by Jim Baker, and it certainly works remarkably well.

BF: Do you think, based on its success, that more systems of this kind will be evolving?

RK: I doubt it. The SX-70 is a fantastic thing anyway, with a mirror that flops down and a viewfinder that reflects off the back of this mirror, and then the mirror jumps up to take the picture. Most people wouldn't even think of doing things in such a complicated way.

BF: The newly introduced Kodak Disc camera is indeed unique with its single aspheric element. That is certainly an advance in the state of the art.

RK: Yes, it is a wide-angle telephoto. To keep the camera thin, the lens had to be short from front to back, and it had to cover a fairly wide angular field. The lens contains four elements, a positive element in front, a thin negative aspheric, another positive element, and finally a large negative field flattener close to the film. It was designed by Don DeJager, who described it at a meeting of the Optical Society last May. It is a most interesting and unusual design.

BF: Where do you see the United States in terms of its status in the international optical community?

RK: With the enormous number of small companies in the Los Angeles area, the Bay area, and in Boston making lenses, the demand for our students is immense. I don't know what lenses they are making, but they're certainly not for cameras; that's all being done in Japan or Singapore. Even Germany is making hardly any more camera lenses. So, this activity must be related to government applications. I don't see what else it could be.

BF: Do you think the United States is keeping up with some of the technology advancements that the Japanese have been pioneering for years?

RK: Probably not. The Japanese are certainly ahead on lenses for SLR cameras, professional movie cameras, and even amateur movie cameras. America has given these up. Bell & Howell and Kodak have both stopped making them. If you want a movie camera, it has to be Japanese now.

BF: Do you think American industry should do something to change that trend?

RK: We've given it up because the competition has become too fierce. I was very surprised when Kodak gave up making movie equipment about two years ago, but they said they couldn't stand the competition. They used to make a sound movie, 8 mm camera; they made the original 16 mm camera in 1923 for amateur use, with reversal processing. But now they have had to yield to the competition.

BF: Do you think it's due to the lower labor rates overseas, or something in a higher level of technology?

RK: When I visited Japan in '64, their technology was essentially comparable with that in this country. Their processes were the same. The care they put into their work, of course, was enormous.

BF: We all know that, unfortunately for the United States, Japanese cars have a better reputation in terms of their quality control and construction. What you are saying is the analogy in optical systems. What can we do about it?

RK: I think it's a matter of the work ethic. The Germans used to have it; they used to admire their work. A German would say, "I can do this," and took pride in what he could do. The Japanese certainly have it now. We've watched Canon and Nikon cameras being assembled. They have a row of girls about 16 years old who do their work with little tweezers, beautiful work. By the time they turn 19, they get married and leave, and more are hired to take their place. Nothing like it in this country, where the girls are thinking about their boyfriends or their clothes or anything other than work. The same problem exists in England, where the optical business is practically gone.

BF: Industry in the countries that are affected, the United States, Germany, England and others, recognizes the pressure from outside—the increased production in countries such as Japan. Surely we should be able to change our approach.

RK: It is the same with the automobile business. Why is it that we cannot make a car in this country that's as good as the Honda? The Chevette, which is a rival to the Honda, costs about the same. My son has one of each. He says the Honda is so much better than the Chevette; there's just no comparison.

BF: Yet, getting back to optics and cameras--the new Disc camera is indeed unique and indeed is a very fine product with a tremendous amount of quality control. So we do have something of a counter technology, if you will.

RK: Yes, fortunately Japan never went into producing inexpensive box cameras. That saved our industry's life. They make only good cameras in Japan. The Disc falls in between. It's a sophisticated camera that does everything automatically, yet it's a popular camera. Polaroid is the only other company that has been working in this field.

BF: How do you feel about the transfer of high technology from the United States? It certainly has had potentially adverse effects relative to our discussion, particularly in electronics and optical systems.

RK: America started the chip business, but quickly the Japanese caught on. When Kodak announced their 110 cameras, within nine months cameras for 110 film were coming in from Japan. They move so fast, it's incredible. Kodak spent four years on the Disc camera. I don't know how long it took to do the 110's.

BF: Do you think U.S. policy regarding technology transfer should be more stringent?

RK: I don't know how you can stop it in a free society, and I would never suggest that we should not be a free society. The only hope is for people to do what they want to do. On the Russian plan they do what the government tells them to do. That would be hopeless. I think as long as we have a free society, we've got to let people pick up ideas where they can, make what they want, sell what they can, compete where they can. I don't see how it can be any other way in a free society.

BF: Yet, this will allow much of the high technology that is being developed in the United States to be acquired by foreign countries.

RK: Yes, but what can we do? The only thing to do is think of something else to make. You can't keep people from copying things if they want to. As long as the stuff is for sale, someone will buy it. If it's only for sale in this country, they'll send a man over here to buy it, and then he'll take it back to Japan—you can't stop it.

BF: In what areas of technology, and particularly optical technology, do you think the United States is going to retain its leadership?

RK: That's a good question. Possibly in space—space applications, space vehicles, space telescopes, big stuff like that. The Japanese don't seem to be going into space very much. The Russians have, of course, but then they have their own optical industry. I don't know why the Japanese haven't gone into space. Perhaps they're too busy with keeping on this earth instead of going out into the sky.

BF: If you were writing a science-fiction story, what type of magic dream device would you conjure up or invent? This is something that may not even be realistic.

RK: I remember seeing a movie where a chap was playing marked cards, and he put on a spectacle which enabled him to get enormous magnification so he could see the marks on the cards. How you could make such a thin, high power magnifier in a spectacle frame I wouldn't know. That must be considered science fiction.

BF: Certainly the technology of holography is something that must have bordered on science fiction some years ago.

RK: Holography is an unbelievable subject—there are things you can do with holography that you never would have suspected.

BF: Holography is a technology that has been looking for major applications for some years now. Do you think it will eventually acquire those applications?

RK: It's beginning to find them. They are using it for particle analysis and detection. Holographic lenses I'm sure will come. Holographic gratings are here already.

BF: Do you think it will reach the public domain in the sense of everyone having a hologram in their living room or holographic movies or something of this sort?

RK: It could. Steve Benton, at Polaroid, has a marvelous show of holograms. They're brilliant and clear and bright colored. He seems to be able to produce holograms that will do anything. There may be a big future there. Holographic lenses have a V-number of about three at the moment, which makes them difficult to achromatize, but you could oppose a plus lens against a minus, even with those high dispersions.

BF: Speaking of achromatic lenses, I remember, from taking your class at the University of Rochester, hearing one evening how the achromatic doublet was patented and the very interesting story relating to its patent and the demonstration thereof. Could you relate that for us.

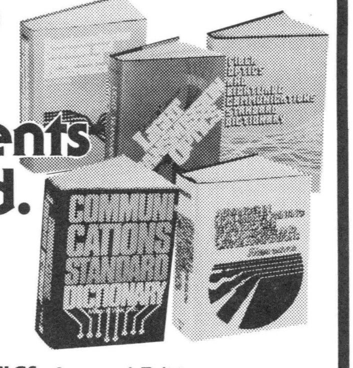
RK: That is all in King's *History of the Telescope,* if you really want the details. Apparently, a lawyer named Hall invented the idea of achromatism. Newton had said previously that achromatism was impossible because the V-number of all glasses was the same. But he was wrong; he just didn't have good measurements. By the time Hall was working, about 1730, he believed that glasses did not all have the same V-number, and therefore it was possible to achromatize. But he was a lawyer and he was a bit secretive. He didn't want to tell the world, so he had the crown element made by one manufacturer and the flint by another. They both subcontracted the work to a third, and the third manufacturer found the same radius of curvature on the two lenses so he laid them together and lo and behold it was achromatic. He told his friends about it, but the thing took time. It took about fifty years to move around, and then Dolland finally ended up making achromatic telescopes for sale. He took out a patent on the idea of an achromat even though he hadn't invented it. The judge ruled that because Dolland had publicized the thing and then manufactured it, and because Hall had kept it a secret, Dolland was entitled to the patent even though he hadn't made the invention. This is a classic decision in patent law. I still question whether it was legal or sensible as a decision, but that was the way the judge ruled.

BF: How do you feel about patents relative to lens systems? If you look in the *Patent Gazette,* you very often see Cooke triplets and similar kinds of lenses?

RK: I review patents for *Applied Optics,* and the editor sends several to me every month. There are 80 or so Cooke triplet patents that I know about. It's incredible. They're not inventions at all. There has been no invention in a Cooke triplet since the first invention was made by Dennis Taylor in 1893.

BF: Why is this and what can we do about it?

RK: If you make an invention, then you should be entitled to a patent. There are only a few hundred thousand real inventions. All the rest of the four and one-half million patents in this country are modifications of existing inventions. The Tessar was an invention, and Paul Rudolph rightfully had a monopoly for 17 years, which he presumably benefited by. Other people had to squirm around his patent by using a triplet in the back instead of two lenses and by employing



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various other schemes. They also patented a number of Tessars, which they could not manufacture, but they could stop Zeiss from making them. Actually, Dr. Mees always said that if the patent system had never been invented, we would be just as well off as we are now.

BF: Many designers will select, as a starting point, an existing patent. The thinking is, if you change the radii ever so slightly in the optimization process, you don't have to worry about infringement.

RK: That is probably true. There have only been perhaps half a dozen lens patents ever challenged in court, and in most of these cases the decision has been that the patent is invalid and not infringed. I could talk about patents for ages. I got mixed up with a patent suit in San Francisco by Perkin and Elmer against another company who had infringed their Offner and Scott patents. It was a jury trial—can you beat that? The judge scarcely comprehended what it was all about, and the jury could not possibly have understood it. So they made the only reasonable decision, namely, that the patent was valid but not infringed. Fortunately, this decision was reversed on appeal, so now Perkin and Elmer have a strong case against any further attempts to infringe these two patents.

BF: This is the system for the microline?

RK: Yes. I often wonder why people take out patents, as most of them are worthless. However, patents are excellent sources of information. I have a stack of patents at home that I have received over the last few years from *Applied Optics* which tell me more about current trends in optics than anything else. Kodak used to patent all its lenses but has suddenly stopped. Many other companies do not patent any of their lenses.

BF: Of course, it has its place in systems like the microline and possibly the SX-70 camera.

RK: Yes, the SX-70 was a novelty and an invention. The microline was an invention. The lens in the Disc camera—I don't know whether Kodak ever will patent it. They publicized it freely, and I suppose if someone wanted to copy it they could.

BF: Other major areas of optics technology involve lasers and fiber optics. These have been mushrooming very substantially in the past years. What are your thoughts about these developments?

RK: I don't know that much about lasers. They have been enormously successful as sources of bright coherent monochromatic radiation in parallel beams, which everybody needed and now we have. But, the fiber business is a strange thing. The whole thing depended on making fibers that would transmit without absorption losses so that you could make them miles long instead of just a few feet. Once that hurdle was overcome, somebody studied the length of time it took to travel down the fiber, and they found that different paths took different times. Then they invented the parabolic cross section of refractive index and eliminated that problem. From now on there seems to be no end to what fibers can do.

BF: Do you see a time when most communication will be by optical fiber?

RK: Yes. As opposed to wires, fibers have many advantages. You can send a carrier wave down a fiber which has the frequency of light, 10^{14} per second, instead of carriers that go on wires, which means you can carry a dozen television signals over one carrier wave on one fiber. As for telephone messages, you could send hundreds or thousands of telephone messages on one fiber, which you couldn't possibly do over wires.

BF: The success of fiber optics communication brings us back to the laser in the sense of laser diodes as the source.

RK: Yes, you need the source. You need the diode source and you need the photocell receptor at the other end.

BF: It appears then that these two areas are two of the more dynamic technologies that have come forth over the past years.

RK: Yes, lasers and fibers account for nearly everything. Holograms depend on lasers, really. All this coherence theory which is being worked on now--image processing and character recognition--all these things come from the possibilities of coherence. The field of modern optics has mushroomed tremendously in comparison to classical optics.

BF: Of course, fibers have been around for many years, but mostly in the sense of illumination and/or coherent bundles for imaging.

RK: But they were short. After three or four feet you'd lost nearly all your signal. That was the limit of what you could do. They used them for medical instruments quite a bit. I'm told that the cost of the fiber bundles is so great that they're going back to lenses in medical instruments.

BF: Do you know the history of the invention of the clad fiber, the step index?

RK: Clad fibers are fairly old. Two articles appeared in the same issue of *Nature,* back in 1954, one by H. H. Hopkins and the other by A. C. S. van Heel. Both men invented the same idea simultaneously. I don't know whether the fibers were cladded, but they must have been. Kapany got into it too while working with Hopkins in England. He came to this country soon after, and got Bausch & Lomb interested in fibers.

BF: I heard that it was invented by a student actually. Maybe that was Kapany.

RK: Yes, probably. Hopkins and Kapany worked together. The problem, of course, was drawing the fibers, cladding them, and then laying them down in ordered bundles, which is very difficult. You can't just wind them up like that. You've got to wind it around a drum once, cut it off, start again, wind around once, cut it off, start again, and so on.

BF: That's for "coherent" bundles?

RK: Yes, though "ordered" bundles is a better name for them. There is no coherence in the ordinary sense. An ordered bundle to transmit optical images is very difficult to make.

BF: Really, fiber technology of the future is being directed more for communication and to a much lesser extent for imagery.

RK: Yes, the ordered bundles have almost gone. They are so expensive and difficult to make, although they are still used for faceplates on cathode ray tubes, or for medical instruments.

BF: Even infrared fibers are becoming very popular for providing a remote high intensity heat source in surgery and related kinds of things.

RK: That is a single fiber. Single fibers are good for convenience, and you can move them around; you can spray out a little radiation at the end. Of course, fiber communications are mostly in the infrared.

BF: I'd like to turn the conversation briefly to military standards.

RK: During the war the military were nuts about scratches on lenses. So Dr. McLeod at Kodak scratched up a plate of glass and placed it in front of a pair of binoculars, but the inspector could not tell the difference.

BF: What do you think of the situation of military standards as they relate to cosmetic effects and scratches and digs and functional criteria?

RK: If they don't make any difference to the image, I don't see that they matter.

BF: Yet the military, where the functional requirement should be the driver, is still, in all likelihood, overspecifying its optics. Is that correct?

RK: They are going to pay more for nothing.

BF: What is the solution?

RK: I don't know, unless you can change military thinking, which is difficult to do.

BF: What about the fact that there is so much confusion in military standards? There are three or four or five different military standards, all of which say very similar things about some of these callouts, and you sometimes see callouts relating to transmissive elements on infrared materials that don't transmit and things of this nature. Do you think there is any hope in sight with respect to military standards?

RK: I doubt it. There are a lot of lawyers who have to protect their jobs after all, and they'll keep writing standards forevermore. The public doesn't like to see a scratch because they feel it represents inferior manufacture. I don't think the military should care whether the optic is scratched or not. After all, a prism

Continued on Page SR-106

ELECTRO-OPTICAL INSTRUMENTATION MARKET FOR QUALITY & PRODUCTION CONTROL IN THE U.S.

The U.S. demand for non-contact, electro-optical instrumentation and systems, used across the wide spectrum of manufacturing for quality and production control, reached $202 million in 1981, and will advance to just under one billion dollars by 1986—a real annual growth rate of 37% over the period.

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A looming question is the level of acceptance by potential end-users of electro-optics over the coming period. This, in turn, raises questions of cost effectiveness, the degree that suppliers are able to educate end-users, and the ability of these systems to stand up in the sometimes hostile environment of the manufacturing process.

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Continued from Page SR-104

binocular that gets caught out in a trench gets all scratched up anyway, but it still works. You can't convince the military, however.

BF: I'd like to turn our discussion back to the university and to education in optics. What about some of your laboratory projects?

RK: One of our projects was to run a course in photography for the benefit of the students. The first thing we had to do, of course, was make a photographic plate. I found a recipe in a book, and we melted the gelatine and put in the sodium chloride and the silver nitrate. We stirred it up and steamed it for a certain time; then we chilled it and squeezed the gelatine through a cloth to make little worms and washed them to get out the soluble salts, remelted it, poured it on a glass plate, and set it on an ice table to chill. Then we put it in a camera and went out and made a photograph. I still have the plate I made. It worked out very well. I remember Jack Tuffer, who worked in the research lab at Kodak Park for years, saying that the only emulsion he ever made was that one. The worst emulsion in the class was made by a student who shall remain nameless. His had thumbprints on it, it had areas of glass where there was no emulsion, and the emulsion varied in thickness which meant varying density. It was terrible. Most of the students did well, however, and it was quite an interesting project.

BF: Wasn't there a requirement that students in the Institute of Optics, up until even the Sixties, take an optical fabrication related class.

RK: Yes, and there still is something of the sort going on. It's very scrappy because there are so many students. Laboratory work is almost gone in the Institute simply because we have so many students. Where we once had a lab that held four students—what can we do with 60? It's fantastic. The undergraduate geometrical optics class has to be done in two sections now because it's so huge. There's not even a room big enough for them.

BF: Do you think that people working in optical design who are coming out of today's educational process have enough understanding of how things are produced?

RK: The only way to really understand something is to do it yourself. Imperial College had a summer school class for a month on making lenses. Actually, it was done at Northampton Polytechnic. There we actually ground and polished lenses; it was most instructive. We made a telescope doublet and an eyepiece. My telescope doublet was very bad; the eyepiece was very good. I still have the eyepiece, which we use as a pocket magnifier at home. Although the telescope objective was terrible, we learned how it could be done and how it should be done and how we weren't doing it. Actually, if we had used test plates and had taken a little longer, we could have made quite a good lens.

BF: What about the educational system in the United States? Let me ask specifically about higher education and the difficulty that universities are now having in attracting capable faculty.

RK: That is a seemingly insoluble problem. The Institute of Optics is losing its faculty like mad. We lost four professors in a year and a half, leaving barely enough to handle the increasing number of students. We just cannot keep people.

BF: What's the solution? This is certainly going to impact the quality of technical education in the United States.

RK: One solution would be for companies like Kodak to lend the universities a man for a year. But they aren't willing to do that because they need the good men. An alternative would be for the companies to finance faculty members because the university is only able to pay them about half the industrial salary. If someone could make up the difference, we might get faculty.

BF: Isn't this something that really has to be done in order for the country to retain its technical leadership?

RK: Yes. There are articles in the literature all the time bemoaning the fact that we can't get faculty members. The competition is too great. If the U. of R. could afford forty, fifty, or sixty thousand dollars a year to get a professor, they could compete with industry. As it is, they're paying about half that and cannot compete. The only other hope might be retirees like me who, after they leave industry, could return to the university to teach. But most retirees don't seem to want to do this. By the time they get to retirement age, they want to go and play golf in Florida.

BF: With some exceptions such as yourself, of course.

RK: There are very few exceptions. Bob Hopkins has retired. He has left the university, and now he's working as a consultant. Everyone is becoming a consultant now except me. I wonder why. There must be something wrong with me, not to become a consultant. I met two men this morning, Institute of Optics graduates, who became consultants. They say it is a great life, lots of work, doing fine. They are not going to be teaching students. The situation is terrible, and the whole of our engineering college is suffering from it. E.E. and mechanical engineering aren't losing people quite as fast as optics. Chemical engineers are much in demand. Chemical engineering students start at about $30,000. It's preposterous; they are not worth it, of course, but that is the going rate, with optics close behind.

BF: What messages or guidance would you have for the optical designer or optical engineer of the future?

RK: Obviously he's got to know everything he can, but there is much more than that. I think he will need a natural curiosity to work out the inwardness of what he's doing. Rather than simply doing a task, he's got to know why he's doing it. In a tutorial yesterday on high speed cameras I tried hard to find out the difference between a drum camera and a camera with stationary film. I talked to one man and asked, "Yes, but why does it . . .?" He could not tell me. Then I talked to another man. "It's simple," he said. "You do this and then that." It all fell into place immediately. The second man understood it; the first man did not. So, I think the message is to understand what's going on all the time, even if it takes you weeks to find out.

BF: In some of the newer fields of modern optics do you think people really comprehend the technology?

RK: A few of them do. A man like Brian Thompson knows what he's doing. He understands everything. Most of the younger fellows, I'm sure, follow the book and don't really understand. There's too much to understand. If you understood the whole of coherence you'd be an Emil Wolf. Wolf and Thompson and people like that, they understand. But the ordinary student, I'm sure, has got to have more time to think, and he's too busy working all day. There's such a lot to do.

BF: You've been retired for about fourteen years now. What have you been doing to occupy your interests over these years.

RK: I've been writing. I wrote the lens design book and have been editing the series for Academic Press, which has kept me quite busy. Shannon and Wyant have taken that over. They've done two volumes and are working on the third. I'm in the process of writing a book for Academic Press on system layout rather than lens design. To date I've written about two-thirds of it. I've also been giving a summer school course for a week each summer now for ten years. People keep coming, so they must want it. About fifty people attended this year.

BF: What are some of your interests outside of the field of optics?

RK: I don't have very many outside interests. I do a little photography, nothing I would consider the arty type of photography—just as needed.

BF: Your life has really been dedicated to optics.

RK: Pretty much. I became interested in the history of photography while working at Eastman House. I wrote a little booklet on the history of all the Rochester optical companies, and then another one on the Bausch & Lomb shutters—of which there are something like fifty. Now I'm working on Wollensak shutters and the history of the Wollensak company. Those things keep me occupied.

BF: You've certainly had a remarkable series of parallel careers both at Eastman Kodak and teaching at the University of Rochester.

RK: Yes that's right. They went along well together. I taught lens design all the time I was at Kodak.

BF: How many students would you say you've taught over the years at the university?

RK: In lens design I've recently listed about nine hundred.

BF: On behalf of approximately nine hundred students who have taken lens design from you, I would like to thank you very much and very sincerely. And thank you very much for this interview.

REVIEW OF RESOLUTION FACTORS IN HOLOGRAPHY

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Abstract. High resolution has long been considered one of the achievable advantages in holography. This has induced the pursuit of research on the application of holographic techniques into several fields. Though the holographic principle ensures the feasibility of high resolution of the order of the radiation wavelength and superresolution, in practice, the obtainable resolution in a holographic experiment remains as one of the most complex features to assess. This is a result of the large number of interactive parameters involved and the difficulty of expressing quantitatively their role upon the resolution expected for the implementation of the conceived experiment. A discussion of the factors that affect resolution is reviewed to establish the range of the physical parameters that should define the experimental setup. A systematic procedure to guarantee a desired resolution is presented, as well as its corresponding implications on the experimental design, namely, angular tolerances ranging to orders of microradians.

1. INTRODUCTION

The utility of the holographic technique in some applications depends upon the quality and resolution of the reconstructed images. Performance of a classical imaging system can be described by the resolution at the image plane and the field of view as refocusing is traditionally used. Holography provides a three-dimensional imaging possibility causing consideration of a transverse and longitudinal resolution.[1,2] Further, an advantage is gained once holographic techniques can provide means to decouple resolution and field of view.[3,4]

One usually is concerned not only with resolution but also with distortion. For clarity, each of these aspects is traditionally treated spearately, although in actual practice degrading of the image will appear with both aspects simultaneously.

The resolution limit depends on many interactive factors, such as the illuminating wavelength, size of the hologram, geometry of optical components and object, object localization, and the particular optical arrangement.

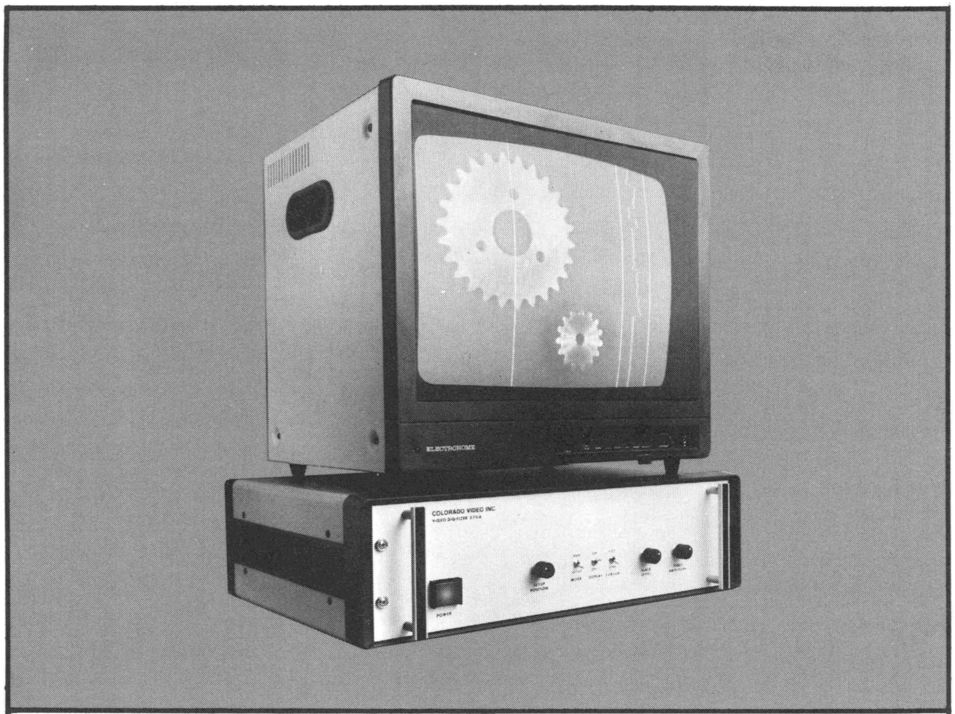
The resolving power is, in general, defined in accordance to the imaging process under consideration. In holography, the characteristics of the particular experimental arrangement have to be taken into account while discussing resolution. The suitable criterion may well depend on whether analyzing in-line or off-axis holograms, of the transmission or reflection type, with plane or volume recording medium, and opaque or transparent objects. Fresnel, Fraunhofer, and Fourier holograms also may differ in resolving power. Scientific literature covers examples of studies of this kind.[6-17] As examples, E. Wolf[15] has calculated that details of amplitude and phase of the scattered field of a transparent object would have a limit of resolution of the order of $3\sqrt{2}/\sin\phi$, where ϕ is the angle that the reference wave makes with the normal to the holographic plate. P. Smigielski[16] has studied the effect of the movement of the object to the resolving power for various kinds of holograms.

Present considerations refer to a general-based discussion and apply more properly to transmission, off-axis, thin holograms of opaque objects.

The ultimate transverse resolution in the image of a holographic system depends upon the numerical aperture of the system,[18] but it is found that the aberrations introduced by practical tolerances will degrade the resolution.

If the hologram is ideal (recording and reconstruction without aberrations) and well adjusted, the resolution of its image is only limited by diffraction of the reconstructed wave at the hologram aperture. The image of an object point is then the well-known Airy diffraction disk,[18] with a diameter χ of the first dark ring given by

$$\chi = 0.77 \frac{\lambda}{n \sin\alpha}, \qquad (1)$$



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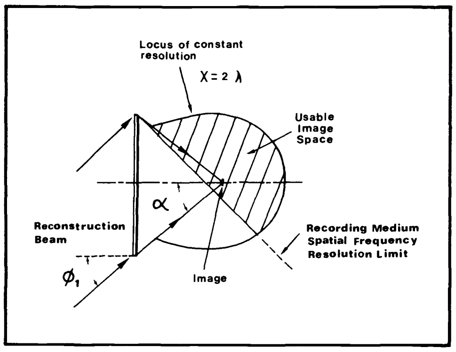

Fig. 1. Reconstruction geometry representation to show the resolving volume—usable space for image reconstruction for a prescribed resolution limit.

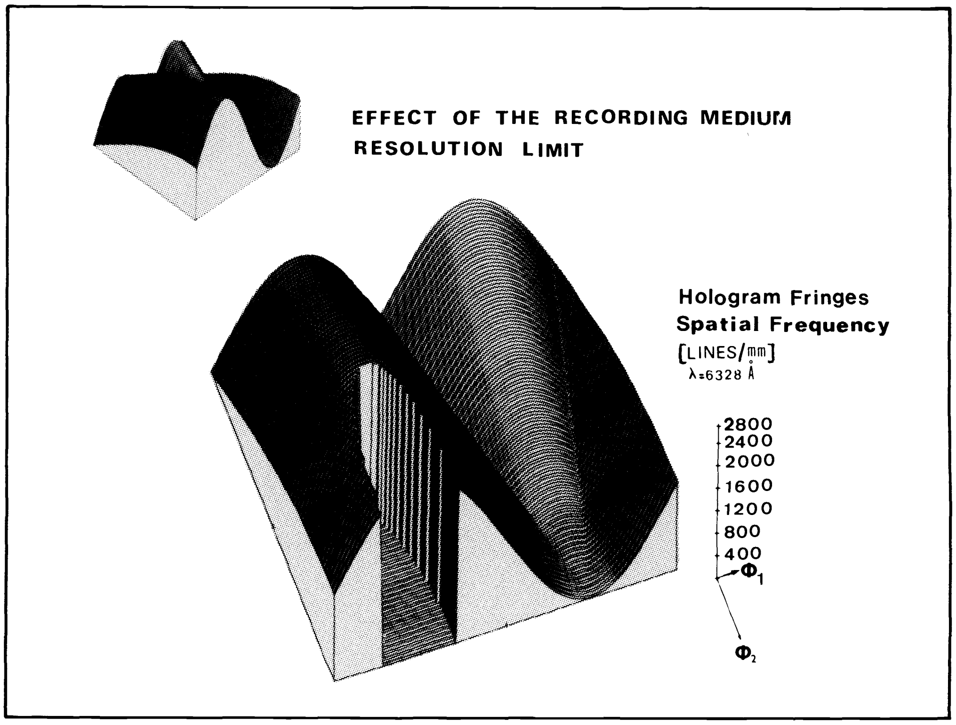

Fig. 2. Mapping of the spatial frequency according to Eq. (4) and showing the effect of recording medium resolution limit.[11]

which is valid for a circular hologram (apart from the numerical factor, which is somewhat arbitrary depending on the object aperture, and sensitivity of the receptor). λ is the reconstruction wavelength, which must be equal to the recording wavelength, and the reconstruction beam is an exact image of the reference beam.[7] The expression n sinα is the numerical aperture (N.A.) of the hologram,[7] where n is the refractive index of the image space, and α is the angle between the axis of the projection cone and the normal of the image plane (Fig. 1), assuming that every object point fully illuminates the hologram. The corresponding longitudinal resolution τ is given by[2]

$$\tau \simeq 0.77 \frac{\lambda}{(n\ \sin\alpha)^2} . \qquad (2)$$

Equation (1) defines a volume,[3] i.e., resolution volume (Fig. 1), wherein the object wave source must be located to attain a certain required resolution in the reconstruction image.

Calculations involving departure from the ideal situation are based on the precept that an image resulting from a nonideal recording and reconstruction will be degraded and formed in a different position from that in the ideal case. In fact, the image formed in an actual nonideal situation will, in general, have all the aberrations normally associated with a lens. A number of factors had to be considered during the recording and playback of the hologram, with the most critical factor being the angular alignment accuracy of the reconstruction wavefront (assuming adequate stability of recording medium).

2. RECORDING GEOMETRY

In theory, there are no more constraints in the holographic principle than those imposed upon any other coherent imaging system.[19] However, there are practical considerations that govern the choice of a recording geometry:

1) propagating distance,
2) holographic recording medium resolving power,
3) hologram thickness,
4) minimization of aberrations,
5) reduction of sensitivity to tolerance errors, and
6) vibrational stability requirements.

These aspects will be discussed in turn.

2.1. Propagating distance

The nature of the diffracted wave is related to the propagation distance.[18] In holography, this leads to the well-known distinction between Fresnel and Fraunhofer holograms. Mittra and Ransom[19] have examined holographic imaging in the two cases in mathematical detail. They predict that holograms recorded in the Fresnel region will reconstruct images which propagate as the original wavefront. On the other hand, a Fraunhofer hologram may not contain enough information to reconstruct the Fresnel region. This has been confirmed by experiments.[20]

2.2. Holographic recording medium resolving power

The ultimate resolution of any imaging system depends on the system aperture.[7] Increasing the size of the holographic system aperture implies a wider spatial frequency spectrum of the interference fringes to be recorded over the hologram. However, the resolution limit of the holographic recording medium sets a limit to the highest spatial frequency recorded. Clearly, the recording geometry must be such that the record remains inside the "resolving volume" (Fig. 1).

There is an upper limit, ν_{lim}, on the resolvable spatial frequency of the recording medium which corresponds to a nonrecording angular region for the interfering beams (Fig. 2).

For off-axis holography, the resolution of the recorder must be at least four times the highest spatial frequency component of the object wave to complete angular separation of twin image diffracting waves and zero-order wave.[21] A reduction of the width of the spatial frequency spectrum can be done by recourse to lens and other Fourier hologram techniques.[12]

The minimum transverse resolution spot[11] at reconstruction will then be χ:

$$\chi = 0.77 \frac{\lambda}{\nu_{\text{lim}} - \sin\phi/\lambda} . \qquad (3)$$

Further, the problem due to the finite size of the recording medium has to be analyzed. In order to minimize the effects due to diffraction at the borders of the hologram—edge effect—a reference beam about three times the hologram diameter is recommended to ensure a rather good reference plane wave over the hologram surface. This reduces the diffraction limit to be taken into account to that resulting from the hologram border, which determines the ultimate image resolution.

2.3. Hologram thickness

According to the recording geometry and hologram thickness, different types of holograms are formed. In particular, thin and volume holograms are to be considered. The latter, in principle, can reach 100% efficiency, but diffraction varies strongly with recording geometry, wave polarization, and hologram thickness.[22,23] Further, the multilayer structure of the spatially oriented fringes in a volume hologram gives rise to spatial modulation of the reconstructed wavefront so that image aberrations can be introduced.[23]

Factors that determine the character of the hologram as a thin or volume type should be examined and consequent effects on resolution taken into account.

2.4. Minimization of aberrations

It has been shown by Leith, Upatnieks, and Haines,[24] Meier,[25] Champagne,[26] and Abramowitz and Ballantyne[27] that under certain circumstances a hologram can form an image free of aberration. Careful matching of reference and reconstruction wavefronts is necessary, and accurate alignment of the holographic plate with respect to the reconstructing wavefront is imperative[11]—the principle of preservation of geometry.[28] The reconstruction geometry reproduces the recording geometry so that aberrations are minimized and diffraction efficiency

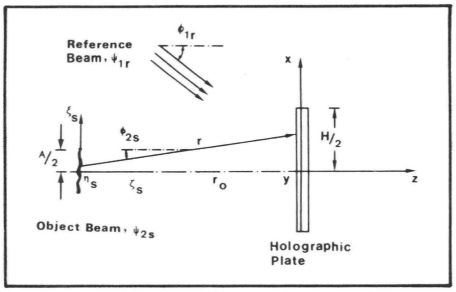

Fig. 3. The notation used to describe the recording of the off-axis hologram.

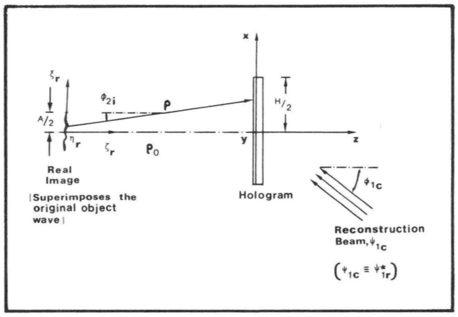

Fig. 4. The notation used to describe the reconstruction of the off-axis hologram (real image projection holography).

is maximized. These conditions are never exactly met in practice. Geometries that lead to a minimum of aberrations should be sought.

The use of a plane wave as the reference wave contributes in several ways to reduce aberrations. The wavefront for reconstruction is also a plane wavefront. This avoids the cumbersome necessity to match curved wavefronts at the hologram plane. In transmission holography, the reconstruction beam must enter the hologram from the back, passing through the plate substrate before it can strike the hologram layer. A plane wavefront encounters no distortion in going through the holographic plate base other than a translational change in the beam direction which can be compensated. This geometry at reconstruction also brings two other advantages. First, the highly convergent wavefront diffracted by the hologram does not focus through the plate base so that aberrations are introduced by refraction. Second, due to the true three-dimensional nature of the recording medium, the maximum diffraction efficiency results with reconstruction in this manner.[7] The angular spectrum being reduced by adoption of a plane reference wave also desensitizes, over the hologram, reposition errors and emulsion shrinkage effects when compared to curved wavefronts.[11]

2.5. Reduction of sensitivity to tolerance errors

The image resolution, and the accuracy in its spatial positioning relative to the hologram, are strongly dependent on the angular alignment of the reconstruction beam relative to the recording reference beam. It is important to consider the adequate angular ranges for the interfering beams to minimize angular misalignment effects. This problem has been analyzed in detail.[11] Given a recording geometry defined in Fig. 3, the reconstruction geometry of Fig. 4, and simplifying the analysis by consideration of the plane waves composing the spectrum of the object wave as interfering with the reference plane, the recorded spatial frequency ν for an incidence within a normal plane to the recording medium is[11]

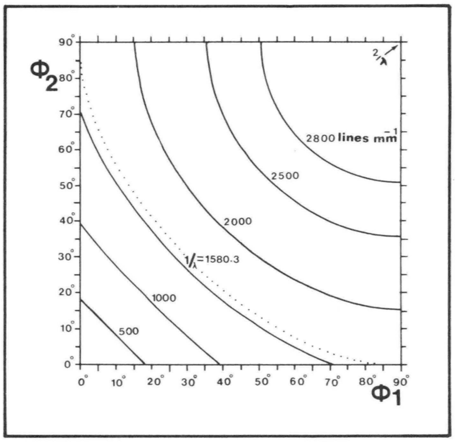

Fig. 5. The spatial frequency isolines (lines/mm) of the interference pattern as a function of the incident angles ϕ_1 and ϕ_2 of the interference plane wave components [Eq. (4)].

$$\nu = \left| \frac{\sin\phi_{1r} + \sin\phi_{2s}}{\lambda} \right| , \tag{4}$$

mapped in Fig. 5, or, in an equivalent formula,

$$\nu = 2 \left| \frac{\sin\phi \, \sin\beta}{\lambda} \right| , \tag{5}$$

where 2ϕ is the angle between interfering beams, and β is the angle of the bisector direction relative to the hologram. Accordingly, the angular error in reconstruction, $\Delta\phi$, for a plane wave component of the object wavefront spectrum, due to a $\Delta\beta$ error misalignment of the hologram, is given by differentiation of Eq. (5):

$$\Delta\phi = \Delta\beta \, \tan\phi \, \mathrm{cotan}\beta \, .$$

On this consideration alone one would make ϕ as small as possible and β as large as possible, i.e., the spatial frequency of the interference pattern as low as possible.

The analysis of the spatial positioning of the image in reference to Fig. 4 leads to a transverse error of

$$\Delta\xi = -\varrho_o \frac{\cos\phi_1}{\cos\phi_2} \Delta\phi_1 , \tag{6}$$

and a longitudinal error[11] of

$$\Delta\zeta = \varrho_o \frac{\cos\phi_1}{\sin\phi_2 \cos^2\phi_2} \Delta\phi_1 \tag{7}$$

for the angular misalignment of $\Delta\phi_1$ on the reconstruction beam relative to the recording beam when a point of the object is at a distance ϱ_o from the hologram and ϕ_1 and ϕ_2 are the in-

One of a series of laser focusing lenses shown mounted in a focusing stage. Each aperature and the related aperature range from F/2 to F/4 with a spot size on axis (in μm) equal to F number.

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cidence angles of the two plane waves interfering at the hologram plane. Therefore, the object should be close to the hologram and its optical axis while having the reference beam with the wide incidence. For $\Delta\phi_1 \simeq 1°$, $\varrho_o = 2$ cm, and $\phi_1 = \phi_2 = 30°$, comes $\Delta\xi \simeq 0.4$ mm and $\Delta\zeta \simeq 0.8$ mm. Reducing positioning errors to the order of the micrometer requires a $\Delta\phi_1$ in the range of seconds of arc.

2.6. Vibrational stability requirements

The problem of vibrational stability intervenes chiefly at the recording stage. The fringe pattern should be stable so that fringe movements are kept below one-tenth of a fringe. For the object wave, this implies very tight tolerances once there is a degree of projective magnification involved.[29] The angular tolerances according to Eq. (5) are given by

$$\Delta\phi < \epsilon\tan\phi\,, \tag{8}$$

and

$$\left\{\begin{array}{ll}\Delta\beta < \epsilon\tan\beta,\ \beta \neq \dfrac{\pi}{2} & (9)\\[2ex] \Delta\beta < \left[1 - \dfrac{1}{(1+\epsilon)^2}\right]^{1/2},\ \beta \simeq \dfrac{\pi}{2}\,, & (10)\end{array}\right.$$

where ϵ is the relative fringe movement tolerance. The object tolerances can be expressed with reference to Fig. 3 and Eq. (4) by a lateral vibrational tolerance of

$$\Delta\xi_s < \left| r_o \frac{\sin\phi_{1r} + \sin\phi_{2s}}{\cos^3\phi_{2s}} \right| \epsilon\,, \tag{11}$$

and a longitudinal vibrational tolerance[11] of

$$\Delta\zeta_s < \left| r_o \frac{\sin\phi_{1r} + \sin\phi_{2s}}{\sin\phi_{2s}\cos^2\phi_{2s}} \right| \epsilon\,. \tag{12}$$

Numerically, for $\epsilon = 1/10$, $r_o = \varrho_o = 2$ cm, and $\phi_{1r} = \phi_{2s} = 30°$, comes $\Delta\phi$ and $\Delta\beta$ of the order of tens of milliradians, and $\Delta\xi_s$ and $\Delta\zeta_s$ of the order of a few millimeters.

Inequalities (8) and (9) express tolerances corresponding to a perturbation on spatial frequencies over the hologram. They can be considered as a range of measurement in double exposure holographic interferometry and time average holography.

Vibrations introduce a change of the optical path of the interference beams that results in a variation of the phase difference between the object and reference waves and consequently a shift of the interference fringes over the hologram. The complete analysis of the effect requires the examination of the particular geometry of the optical arrangement. According to Fig. 3, the transverse tolerance for the object is the order of

$$\Delta\xi_s < \epsilon\frac{\lambda}{\tan\phi_1}\,, \tag{13}$$

and the longitudinal tolerance is given by

$$\Delta\zeta_s < \epsilon\frac{\lambda}{\cos\phi_1}\,. \tag{14}$$

Expressions (13) and (14) were derived without taking into account the optical path variation on the object illumination beam, which further tightens the tolerances. The hologram of a transparency is less sensitive to object motion than the hologram of an opaque object.

Analogously, the vibrational tolerances for the holographic plate can be found from

$$\Delta\xi_H < \epsilon\frac{\lambda}{2(\sin\phi_1 + \sin\phi_2)}\,, \tag{15}$$

and

$$\Delta\zeta_H < \epsilon\frac{\lambda}{\cos\phi_1[1 + \cos(\phi_1 + \phi_2)]}\,. \tag{16}$$

For $\epsilon = 1/10$, $\lambda = 0.6$ μm, and $\phi_1 = \phi_2 = 30°$, we get $\Delta\xi_s$, $\Delta\zeta_s$, $\Delta\xi_H$, and $\Delta\zeta_H$ of the order of tenths and hundredths of micrometers, respectively.

This kind of analysis extends to the stability of all the components of the optical arrangement with adequate adaptation. It is seen that to use a design angle much in excess of the resolving power required unnecessarily reduces these tolerances. The projective magnifications affect differently these tolerances.

These tolerances ensure no loss of the diffraction pattern. However, there is a further aspect of vibrational stability related to the loss of resolving power which is, in principle, comparable to the vibration amplitude.[16,29] The achievement of high resolution imposes, then, very tight control vibrational stability, in particular, the avoidance of microphonisms on the different components of the experimental arrangement.

In conclusion, a geometry is recommended that meets the following criteria:

—records in the near field of the diffraction from the object;
—uses a plane reference wave;
—the reference and object beam strike the holographic recording layer before going through the holographic plate base;
—the object is placed as near as possible to the holographic plate;
—the reference beam has the wider angle of incidence;
—the holographic plate normal approximately bisects the angle between the reference and object beams.

3. GEOMETRICAL ABERRATIONS

Aberrations strongly degrade image fidelity. Holograms, in practice, give rise to all the geometrical aberrations.[25] In addition, there are aberrations associated with tolerance repositioning errors.

The primary wave aberrations of geometrical optics—the classical aberrations of Seidel[18]—vanish for holograms with a unit magnification.[30] However, lack of perfection in the setup will produce small departures from unit magnification and hence bring in the aberrations, albeit at a low level, but with increasing effect with hologram aperture (the spherical aberration as H^4, the coma as H^3, the astigmatism and curvature of field as H^2, and the distortion as H^{3}[30]).

Aberrations are introduced whenever any of the system parameters are changed between recording and reconstruction. An understanding of the aberrations of a hologram is vital to the achievement of high resolution imaging. The weight of the major aberrant factors has to be identified so that a design leading to minimization of the degrading effects can be made. Three main causes will be considered:

1) effect of source spectral line bandwidth,
2) wavefront curvature error, and
3) orientation and collinearity tolerances.

The effects of source spectral line bandwidth $\Delta\lambda$ for the laser source used are, in general, negligible[11] once large aperture holograms are used for high resolution. The angular spread $\Delta\phi_{2i}$(Fig. 4) resulting from the finite line bandwidth $\Delta\lambda$ is of the order of

$$\Delta\phi_{2i} \simeq 2\frac{\Delta\lambda}{\lambda}\sin\phi_{1c}\,. \tag{17}$$

It becomes equal to the spread caused by diffraction for a hologram effective aperture of the order of 20 cm and 5 cm for the HeNe and argon laser, respectively.[13]

The wavefront curvature error results from the imperfect collimating of the reference and reconstruction beams, inhomogeneities of the media traversed by the beams, and the interface's departure from plane surfaces seen by the beam. The tolerable curvature error is defined by a wavefront flatness within a quarter wavelength.[11] A required extension of the analysis concerns the degree of rigidity required from the holographic plate. The plate will be mounted in a holder and submitted to stress. Care should be taken to ensure a tolerable deformation.[11]

The main contribution to wavefront phase errors results from refractive effect at the boundaries of the media the beams have to go through. In this analysis it is most important to consider the holographic plate and its effect on image quality, i.e., how flat and homogeneous the holographic plates have to be. It was proved[11] that the average optical thickness of the holographic plate should not present variations above λ, and the amplitude on phase fluctuations should be below $\lambda/10$.[31]

Orientation and collinearity tolerances express the conditions to be met by reference and reconstruction waves once we have considered the use of plane waves. It is found that the image is extremely astigmatic for only slight angular rotations from the aligning position of the beams. If one accepts the criterion that the image displacement should not exceed one-half of the diameter of the circle of confusion,[18] the tolerance for the beams' collinearity,[11] $\Delta\phi$, will be on the order of

$$\Delta\phi < 0.77\frac{\lambda}{2H}\,, \tag{18}$$

where H is the hologram diameter. In practice, the tolerance limit being on the order of microrads represents a rather stringent condition so that means of ensuring the reference and reconstruction beams' collinearity as for aligning the hologram with respect to the reconstruction beam have to be used.[32]

4. HOLOGRAPHIC RECORDING MATERIAL

There is no ideal holographic recording medium, so that in a real system anomalies are expected. Refractive index changes, which might occur after exposure, can be compensated.[33] However, fringe distortion and shrinkage effects represent severe and complex problems. The fringe spacing may vary during the recording medium processing, and the residual stresses in the recording medium can be relieved during processing, thus

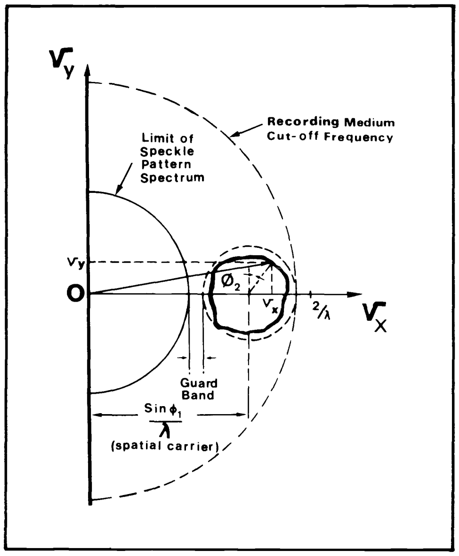

Fig. 6. Spatial frequency spectrum for basic off-axis holographic system. The vector length from the origin, O, represents the magnitude of the spatial frequency components. The vector orientation is the direction normal to the set of fringes under consideration. A "guard-band" between speckle pattern and holographic pattern components is observed to the reconstruction of an image free of speckle overlapping.

distorting the fringe orientation.

The study of the problem has been done by several authors.[32,34] It was found that shrinkage introduces strong aberrations. A low carrier frequency should be chosen to lessen the effect of emulsion shrinkage, and the diffraction planes should be preferably normal to the surface of the emulsion. A nonwet processing of the recording material capable of producing a rigid and stable hologram is most desirable, while internal stress should be relieved prior to exposure.[11] Alternatively, the holographic plate can be immersed in an index-matching liquid both for hologram construction and image reconstruction.[8]

5. DIFFUSE ILLUMINATION

When a coherent light beam either is reflected from a rough surface or propagates through a medium with random refractive index fluctuations, a random intensity distribution arises—diffuse coherent illumination. The observed distribution is known as speckle pattern.[35]

Holograms of nondiffused objects are rarely used because the reconstructed image would suffer from other degrading artifacts arising from dust and imperfections both on and in the holographic material and in the reconstruction optics. Diffuse illumination is used to store the hologram, making it relatively immune to imperfections and sufficiently insensitive to small translations of the reconstruction beam.[11] Another advantage relates to the improvement of the dynamic range of the reconstructed image and consequently a much more uniform depth of modulation over the holographic plate.

Care should be taken to restrict the inconvenience of diffuse illumination.[11] The recording geometry has to be chosen in such a way that the reconstructed image will be free of overlapped flare light due to the recorded speckle pattern component. This situation is achieved whenever the spatial frequencies involved in the holographic interference pattern are higher than any of the speckle pattern components (Fig. 6). The angular relationship between the reference beam and rays emanating from the center and extremities of the object has to be chosen so as to occupy the available range of spatial frequencies.

The object and the holographic plate are illuminated with coherent light. Due to the speckle pattern nature, the coherent image consists of a cigar-shape[1] diffraction-limited distribution, i.e., of diameter and length approximately given by expressions (1) and (2), respectively. In other words, the speckle grain works as the information quanta.[2] Therefore, the resolving power comes to about half the diffraction resolving power,[36] and coherent illuminated systems will require twice the aperture for equivalent resolution when incoherent illuminated.

6. FURTHER COMMENTS

The present discussion has not yet considered other factors that are important to the complete analysis of resolution in the holographic process. They include the following: the vectorial nature of light so that polarization has to be taken into account,[37] the nonlinear response curves of the recording material bringing higher order terms into attention,[25] the hologram thickness originating a volume effect,[23,38] and the recording medium grain and system noise.[12]

Beyond transverse and longitudinal resolution in holographic image analysis, the field of view has to be considered. These restrictions, in practice, appear combined so that a compromise is required, usually through the analysis of the space-bandwidth product.[1,12,39]

A general description of the imaging properties considering all these factors is still the subject of much research.

7. ASSESSMENT OF ATTAINABLE RESOLUTION

Any calculation concerning the resolution limit of an imaging system is at best a guide to expected performance.

The upper bound to the resolution limit is determined by four factors:

1) hologram aperture—determines the ultimate resolution;
2) resolution limit of the recording medium;
3) aberrations due to lack of perfection of the experimental arrangement, fringe pattern changes during hologram development, and deviation of the hologram from an optically flat plate;
4) errors in obtaining exact matching of reference and reconstruction beams.

Whichever of these resolution limits comes first, it will set the resolution limit of the holographic imaging system.

Critical factors in obtaining high resolution images are the angular alignment of the reconstruction beam, the holographic plate flatness, and shrinkage control.

The best resolution obtained with visible light by holographic techniques has been of the order of a few micrometers, i.e., comparable to the wavelength (and some tens of micrometers for longitudinal resolution)[1,4,6,8,11,12,14,16,17,21,40] without recurring to superresolution.[10]

The hologram area increases with the area of the object (as 1/N.A.)[3] and its volume (as 1/N.A.)[5] once information has to be encoded over the hologram surface. Nevertheless, most of the time only certain points of the object are of interest. Holography already provides techniques to study their relative positions and movements with accuracy greater than $\lambda/100$.[1,21,41]

8. CONCLUSION

The analysis of the factors involved in high resolution holography has been reviewed towards an experimental approach. The large number of parameters were examined in their mutual influence on resolution of the image, and the experimental implications were observed. Experimental design suggestions were proposed to improve resolution of holographic systems.

9. ACKNOWLEDGMENT

The research work was partially supported by a research grant of INIC through Centro de Física da Universidade do Porto.

10. REFERENCES

1. H. J. Caulfield (Ed.), *Handbook of Optical Holography,* Academic Press, New York (1979).
2. N. Abramson, *The Making and Evaluation of Holograms,* Academic Press, New York (1981).
3. W. H. Carter and A. A. Dougal, J. Opt. Soc. Am. 56, 1754 (1966).
4. H. Royer, P. Lecoq, and E. Ramsmeyer, Opt. Commun. 37, 84 (1981).
5. G. Toraldo di Francia, J. Opt. Soc. Am. 45, 497 (1955).
6. G. W. Stroke and D. G. Falconer, Phys. Lett. 13, 306 (1964).
7. E. B. Champagne and N. G. Massey, Appl. Opt. 8, 1879 (1969).

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8. R. F. Majkowski and A. D. Gara, Appl. Opt. 11, 1867 (1972).
9. S. S. Hsio, J. Opt. Soc. Am. 63, 1108 (1973).
10. M. Ueda, T. Sato, and M. Kondo, Opt. Acta 20, 403 (1973).
11. O. D. D. Soares, "Holographic Coupler for Waveguide Arrays," Ph.D. Thesis, Univ. London (1976).
12. J. B. DeVelis, *Theory and Applications of Holography,* Addison-Wesley Pub. Co., Reading (1967).
13. H. M. Smith, *Principles of Holography,* Wiley Interscience, New York (1969).
14. R. A. Belz, "Resolution Limits of Fraunhofer Holography," Arnold Engineering Development Center, Technical Report AEDC-TR-70-23 (May 1970).
15. E. Wolf, J. Opt. Soc. Am. 60, 18 (1970).
16. P. Smigielski, "Étude des Projectiles en Vol Hypersonique et de leurs Sillages par des Methodes Holographiques," Thèse, Université de Besançon (1973).
17. G. Vanhomwegen, "Dependence of Transverse and Longitudinal Resolution on Some Parameters Defining the Set-up in Holography," Photonics Applied to Nuclear Physics:1; European Hybrid Spectrometer Workshop on Holography and High-Resolution Techniques, CERN, Geneva (1982).
18. M. Born and E. Wolf, *Principles of Optics,* Pergamon Press, New York (1975).
19. R. Mittra and P. L. Ransom, "Imaging with Coherent Fields," Symposium on Modern Optics, Polytechnic Institute of Brooklyn, Vol. XVIII, 619 (1967).
20. H. J. Caulfield and D. D. Eden, Amer. J. Phys. 34, 439 (1966).
21. R. J. Collier, C. B. Burckhart, and L. H. Lin, *Optical Holography,* Academic Press, New York (1971).
22. H. Kolgelnik, Bell Syst. Tech. J. 48, 2909 (1969).
23. L. Solymar and D. J. Cooke, *Volume Holography and Volume Gratings,* Academic Press, New York (1981).
24. E. N. Leith, J. Upatnieks, and K. A. Haines, J. Opt. Soc. Am. 55, 981 (1965).
25. R. W. Meier, J. Opt. Soc. Am. 55, 987 (1965).
26. E. B. Champagne, J. Opt. Soc. Am. 57, 51 (1967).
27. I. A. Abramowitz and J. M. Ballantyne, J. Opt. Soc. Am. 57, 1522 (1967).
28. H. W. Rose, "Holographic Lens Systems," U.S. Air Force Avionics Laboratory Technical Report AFAL-TR-73-101 (1973).
29. G. L. Rogers, J. Sci. Instrum. 43, 677 (1966).
30. J. A. Armstrong, IBM J., 171 (May 1966).
31. O. D. D. Soares and A. M. P. P. Leite, Proc. SPIE 177, 44 (1979). O. D. D. Soares and A. M. P. P. Leite, Proc. SPIE 212, 17 (1979).
32. O. D. D. Soares, Appl. Opt. 18, 3838 (1979).
33. A. A. Friesem and J. L. Walker, Appl. Opt. 8, 1504 (1969); O. Bryngdahl, Appl. Opt. 11, 195 (1972).
34. A. D. Gara and F. T. S. Yu, Appl. Opt. 10, 1324 (1971); F. T. S. Yu, *Introduction to Diffraction, Information Processing and Holography,* The MIT Press, Cambridge, Mass. (1973).
35. J. C. Dainty, (Ed.), *Laser Speckle and Related Phenomena, Topics in Applied Physics,* Vol 9, Springer-Verlag, New York (1975).
36. Y. I. Ostrovsky, M. M. Butusov, and G. V. Ostrovskaya, *Interferometry by Holography,* Springer-Verlag, Berlin (1980).
37. K. Gasvik, Optik 39, 47 (1973); A. W. Lohmann, Appl. Opt. 4, 1667 (1965); R. W. Rose, T. L. Williamson, and S. A. Collins, Appl. Opt. 9, 2394 (1970).
38. M. R. B. Forshaw, Opt. Acta 20, 669 (1973).
39. A. W. Lohmann, "The Space-bandwidth Product Applied to Spatial Filtering and to Holography," Summer School of the Univ. of Michigan, Ann Arbor (1966).
40. M. E. Cox and K. J. Vahala, Appl. Opt. 17, 1455 (1978).
41. C. M. Vest, *Holographic Interferometry,* John Wiley and Sons, New York (1979).

Laboratory Report

CHINA: XIAN INSTITUTE OF OPTICS AND PRECISION MECHANICS

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After years of hard work and struggle, China's progress includes opening the doors for Western tourists. Mary and I went with two 35 mm cameras, including a telephoto and a 17 mm "fisheye" lens, and plenty of Ektachrome. Tour buses throughout the trip were air-conditioned, with windows that allow good picture taking also. Tourists may also buy 2×2 slides in sets with English booklets for most of the places of interest.

In Beijing (Peking) we saw the Forbidden Palace where the *Marco Polo* film was made. The city has a subway. No autos may as yet be owned privately, but bicycles may be owned on very favorable terms. Westerners travel on first- or second-class status on all tours. After our train trip to the Great Wall, the rest of our travel was by air or boat.

Our group had no trouble with x-ray inspection and film. We flew to Xian (Shaanxi Province), known for the Eighth Route Army that had headquartered there under Chou En-Lai, Chu Te, and others. Xian is also the eastern end of the silk trail of long ago. The discovery of the "Terra Cotta Army" buried long before the pyramids of Egypt is now attracting many visitors. Our hotel was twelve stories high, three months old, and complete with modern elevators, air-conditioning, modern plumbing, phones, and restaurant, as well as having a view of the pagoda where Buddhism was reported to have started, the Xian Institute of Optics and Precision Mechanics of the Academy of Science, and a number of solar hot water heater panels.

Richard Wollensak, then president of SPIE, prepared a letter of introduction and I was invited to present a seminar, which was attended by a standing room only audience. Since I do not know a word of Chinese, the seminar required two-way translation.

We began with a discussion of my background in precision optical design and manufacture, including performance. Rotating mirror cameras such as the Beckman & Whitley cameras were critiqued, including such factors as helium availability, mirror and turbine self-destruction, relay lens thermal warp, and image deterioration thereby. Then there was a brief discussion of timing comedy by capping shutters.

This led to sweeping image or so-called streak cameras. As I had designed the optics of the Beckman & Whitley model C339 continuous writing camera, the novel design of the whole rig was sketched. The vacuum interior includes a three-sided gas-driven turbine and a two-mirror slit-image relay system. Mounting the 300 mm diameter mirror was found to be a thermal and shock mount problem. This slit relay design took the f/8 objective lens ray bundle which corrected in part for film track and mirror vignetting by sending f/4 onto the film. The film track was a particular problem solved by Kingsley Chan.

A brief discussion of time-lapse (or "time-compression") cameras may have been a surprise. As the building was undergoing much construction, I noted that time-lapse records are being used by engineers to monitor progress, safety, etc. The films are then used to show the progress of a three-month job in a one-hour class. The nearby modern solar panels were commended as a sign of good energy use.

A brief review of the different problems experienced by U.S. business centered on growth, failure, and the problems of communicating with ease and accuracy.

A tour of their laboratory showed some of their equipment, which they also export. Their model ZFK 500 air-driven rotating mirror camera has a top framing rate of 4×10^{-6} fps for 81 frames of 9×9 mm. Their model LBS-16A high speed prism camera uses a single shaft for sprocket and prism for operation up to 8000 fps, whereas their LBS 2000 and GS240/35 high speed cine type cameras provide 35 mm film speeds of 200 to 4000 fps and 50 to 240 fps with pin registration of their intermittent motion. Their design and workmanship appear to be of very good laboratory quality.

I was shown their image converter high speed framing tube out of the camera. As I had some time ago made faceplates for such things, we discussed photocathode and faceplate glass surface chemistry and optical finish problems.

Professor Gong Zutong was not in good health when our visit occurred. He is well beyond retirement as we think of it in the U.S., but it must be noted that the "Cultural Revolution" shut down most universities, institutes, schools, and sophisticated technology in general, such that an age gap exists among scientific and engineering personnel. Thus, vice-professor Chen Junren and associates are fortunate to have an older expert surviving to avoid having to start all over from scratch. I would have liked to spend more time at the Xian Institute, but then my wife would have had to leave me to have a place reserved to stay, and also the tour reservations into Xian were booked solid.

China now manufactures a twin-lens reflex camera (6×6 cm) and a 35 mm single-lens reflex camera, both of metal construction, both under the trade name of Seagull as sold in the U.S. Trade exhibitions have spread in China. I was fortunate to see one of these exhibiting visual optical instruments for medical use. Good quality was shown, but not much chrome nor advanced coatings. Chinese friends say that lasers are made in China, and related equipment is beginning to appear.

While we were in our tour bus, we saw a large billboard (like our highway advertising boards), which said in Chinese and *also English*: "One is better," showing happy parents with one child. This government declaration caused much discussion in the tour group. A few days later we learned that the census was being taken and all evidence pointed to a population of more than *one billion.* From 1949 to 1982, life expectancy had *doubled.*

We flew next to see the panda area, and then on to Chongqing (Chunking). Bomb shelters from the 1940's have been converted to storage, laundries, etc. The Yangtse River divides the city, with only an aerial ski-lift type gondola to supplement the slow ferry boats. We bought fresh Ektachrome 200 (at U.S. prices) and left the next morning by modern river boat. The river has a caramel color due to topsoil erosion. We were told that an emperor who lived many years B.C. saw that his subjects were starving and ordered trees cut down to allow food crop production. Thus, the topsoil washes away, as famine pressure forces crop cultivation even on 45 degree slopes.

Each Chinese adult is now required to plant a new tree each year to reverse the rate of erosion. By such conservation measures and its zero population growth policy, China shows its struggle for a better life.

We left the Yangtse at Wuhan and visited the university there at the time of college entrance examinations. Everyone agreed that more students should go through college, but the cost restrains the increase.

The China International Travel Service arranged for a farewell feast in Shanghai as a gesture of goodwill. They even served baked Alaska! Also, the Chinese people are eager to learn English, whether by television, school, cassette tape, or by talking to an English-speaking tourist. We were stopped in many places to talk English and make friends.

Conference Report

10TH INTERNATIONAL OPTICAL COMPUTING CONFERENCE, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APRIL 6-8, 1983

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Despite the explosive proliferation of optics journals and books, communication among the world's leaders in optical computing and processing has been difficult and slow. By joining together, the IOCC and ICO hope to make an effort to change that situation through this conference. The major contributors from four continents were expected to meet at the Massachusetts Institute of Technology to present their work and to plan the future. The local arrangement committee worked especially hard to arrange housing for foreign participants at the homes of local scientists and engineers. A special tour of the Old Sturbridge Village was added to the group luncheons and reception to increase social contact among the participants. These extra efforts greatly enhanced the atmosphere of the conference.

The technical program was quite full and was organized into eight sessions. The first session was a plenary session; six others were grouped into three sets of parallel sessions, and there was one poster session. Professor A. W. Lohmann opened the conference with a keynote address, in which he strongly emphasized the importance of hybrid processing and suggested that a judicious "stealing" from another discipline (e.g., electronic digital processing) when profitable, and cooperation when necessary, can enhance the chances of success for optical techniques. The rest of the papers in the plenary session and one in the afternoon session were devoted to what can be called "optical number crunching systems." Papers by P. Chavel, et al., Y. Ichioka and J. Tanida, H. Barr and S. Lee, and A. Huang dealt with different aspects of optical digital processors. The first paper considered the optical interconnection between optical logic gates; the next two papers discussed different optical logic implementations, and the last paper studied the algorithm aspect of digital optical processors. Six papers in the afternoon session were on different aspects of optical matrix algebraic processing, and included a survey on existing architectures of systolic array processors (by R. Athale); eigenvalue calculation and inversion of circulant matrices using coherent optical systems (by Q. Cao and J. Goodman); computing with the accuracy of binary arithmetic using an analog, time-integrating acousto-optic system (by P. Guilfoyle); integrated optics approaches to matrix multiplication (by C. Verber); and guidelines for efficient use of optical systolic array processors (by D. Casasent).

The parallel sessions on Devices and the following morning's session on Inverse Scattering and Image Processing were affected by a number of cancellations, mostly by authors from Eastern countries. However, there were quite a few interesting papers in these sessions, e.g., computer-controlled optical switching network (by B. Clymer and S. Collins) and tomographic and projective reconstructions of 3-D image detail in inverse scattering (by N. Farhat). The incoherent optical processor described by A. Tai and C. Aleksoff is capable of performing Fourier transforms on 1-D incoherent inputs using directly the light emanating from the object scenes (thereby removing all limitations imposed by input transducers) and an achromatic grating interferometer.

The last day of the conference had a session on

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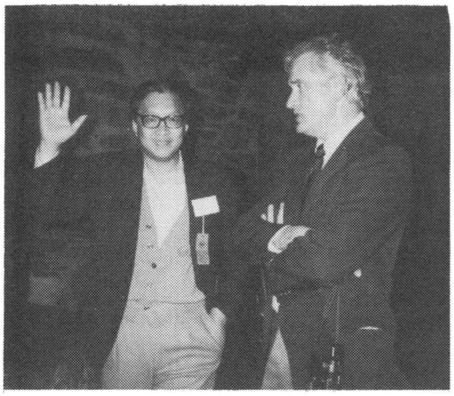

Fig. 1. (left) Sing Lee, University of California, San Diego and (right) Lloyd Huff, University of Dayton Research Institute.

Image and Signal Manipulation and a session on Applications which were scheduled in parallel with a poster session. The papers that caught our special attention included "Coherent optical Fourier analysis of multidimensional signals represented by sequences" by J. Hofer-Alfeis and R. Bamler of Technological University of Munich, where 3-D or 4-D signals were represented as a 2-D set of sectional images; "How useful are the computations of moments in the presence of object noise and obscuration for image analysis" by C. Giles and H. Szu; and "Fabrication of MOSFETs in CW laser recrystallized silicon films on $LiNbO_3$ substrates" by R. Reedy and S. Lee, where a material problem was solved for combining the major advantages of integrated optics with those of integrated electronics.

Fig. 2. (left) E. Marom, Tel Aviv University and (right) A. Tai, Environmental Research Institute of Michigan.

The conference drew 179 participants. Among them we were delighted to see representatives not only from many foreign countries, but also from several U.S. industrial companies with surging interests. If the field of optical computing is heading toward an optimistic future, as expressed in the preface of the conference proceedings by our program chairman, H. J. Caulfield, the sustained interests and increased R&D efforts by industrial companies will be very much welcomed and needed.

Fig. 3. (left) R. Pryputniewicz, Worcester Polytechnic Institute and (right) D. Vukicevic, University of Zagreb.

Book Reviews

Handbook of Laser Science and Technology, Vol. I: Lasers and Masers

Marvin J. Weber, Ed., 568 pp., illus., index, references. ISBN 0-3493-3501-9. CRC Press, Inc., 2000 Corporate Blvd. N.W., Boca Raton, FL 33431 (1982) $105.00.

Reviewed by David C. Brown, TRW Inc., One Space Park, Redondo Beach, CA 90278.

It has been over a decade since the publication of the first CRC handbook on lasers. This new handbook, edited by Marvin Weber of Lawrence Livermore National Laboratory, has been issued in two volumes, owing to the explosive growth that laser science and technology has sustained in the past decade. Volume I, which is the subject of this review, contains 542 pages as well as an index, and is divided into six separate sections. Section 1 (Introduction) is concerned with a review of the types of laser sources and their comparison. Section 2 is on Solid State Lasers, including crystalline, semiconductor, glass, and fiber Raman lasers. Section 3, entitled Liquid Lasers, includes organic dye lasers as well as inorganic liquid lasers. In Sec. 4 (Other Lasers), free-electron lasers and x-ray lasers are covered. Section 5 (Masers) deals with masers and contains a good discussion of masers in nature discovered in outer space. Section 6 (Laser Safety) is a compendium of hazards encountered from optical radiation, the use of laser power supplies, as well as various agents. Volume I contains a forward by Charles Townes, one of the founders of the science of lasers and masers, and a preface by Weber. Volume II is concerned specifically with gas lasers and is divided into four sections, the first on neutral gas lasers, the second on ionized gas lasers, the third on molecular gas lasers, and the final is a tabulation of laser wavelengths.

The handbook begins in Sec. 1 with a comparison (by W. F. Krupke) of the various classes of laser sources and includes a useful figure (1.1.1) of the operating wavelengths of lasers in the 120 to 12000 nm spectral region, tables (1.1.3 and 1.1.4) comparing the properties and performance of cw and pulsed lasers respectively, as well as a figure (1.1.3) of the spectral tuning ranges for various tunable lasers. The first subsection of Sec. 2 (2.1.1) is an excellent article on paramagnetic ion lasers written by P. F. Moulton. It begins with a discussion of the characteristics of different classes of paramagnetic ion lasers, including the trivalent and divalent rare earths, the iron group, and the actinides. The article contains Dieke energy level diagrams for rare earths in crystals and for free ions, numerous energy level diagrams for laser transitions in trivalent rare-earth and iron group ions, absorption spectra of various rare-earth ions in YAG (which would be more useful if the ion number densities were given), the fluorescence spectra of a number of important lasers, and a discussion of energy transfer. This well-written, useful article concludes with a number of extensive well-documented tables, beginning with Table 2.1.1.1 on insulating crystal laser hosts, Table 2.1.1.2 on laser crystals, Table 2.1.1.3 on sensitized lasers, Table 2.1.1.4 on cascade lasers, Table 2.1.1.5 on cw lasers, Table 2.1.1.6 on Q-switched lasers, Table 2.1.1.7 on mode-locked lasers, and Table 2.1.1.8 on broadly tunable lasers.

The second subsection (2.1.2) in Sec. 2, authored by S. P. Chinn, is concerned with stoichiometric lasers. After a fairly brief introduction to the properties of such lasers, including optical excitation and concentration quenching and a review of the important Nd laser, the reader will find two useful tables, the first (Table 2.1.2.1) tabulating the properties of stoichiometric laser crystals and the second (Table 2.1.2.3) listing the operation of various stoichiometric lasers to date.

Section 2.1.3, written by Lin F. Mollenauer, is a very brief introduction to color-center lasers and contains very little information not already available elsewhere [for example, in Quantum Electronics Part B, and in *Methods of Experimental Physics,* Academic Press, New York (1979)].

Section 2.2 on semiconductor lasers, contributed by Henry Kressel and Michael Ettenburg, is an excellent introduction to the essential physics of semiconductor lasers and concentrates in particular on injection lasers. Discussed therein are the operating principles of semiconductor lasers, externally excited lasers, diode lasers, radiation properties, gain coefficient and threshold conditions, spectral emission, materials, modulation, and reliability.

In Sec. 2.3 one of the finest chapters in the handbook appears, concerning glass lasers and authored by S. E. Stokowski. After reviewing those rare earths that have been found to form lasers in glass and their spectroscopy, the operating modes, techniques, and performance characteristics of neodymium oscillators and amplifiers, are discussed.

Tables of the performance of such devices are included. Reviewed next are the general properties of laser glasses, in particular, spectroscopic properties rationalized by the use of Judd-Ofelt theory, nonradiative decay, linear and nonlinear indices of refraction effects of glass composition, concentration quenching, sensitization, laser damage, and solarization. Following that, the specific laser glass properties of thirteen laser glass compositions are tabulated in Table 2.3.12, selected from a large number of available compositions, but including important silicate, phosphate, and fluorophosphate glasses. This article may be viewed as a condensation of the voluminous data on laser glasses published by workers from Lawrence Livermore National Laboratory concerning the optical, physical, and mechanical properties of laser glasses, as well as their nonlinear indices.

Section 2.4 on fiber Raman lasers by R. H. Stolen and Chinlon Lin is an interesting article on a fairly new laser in which a pump laser interacts with a long glass fiber to produce stimulated Raman scattering. The article discusses single-pass fiber Raman lasers, fiber Raman oscillators, and calculation of the threshold power for such oscillators. The final section (2.5) of Sec. 2 is an extensive table (2.5.1) of the wavelengths of solid-state lasers spanning the spectral range 0.286 to 32 μm.

Section 3.1 on organic dye lasers, by R. Steppel, begins with a discussion of excitation and relaxation processes in organic dyes, moves on to a good discussion of the correlation between structural features of such dyes and various physical processes, and ends with an exhaustive table (Table 3.1.6) of the structure and lasing properties of organic dyes. Tuning curves for dye lasers using various pump sources are also included. This article contains one of the most useful discussions of dye degradation to appear in the laser literature.

A very good section on inorganic liquid lasers, authored by H. Somelson may be found in the second section (3.2) of Sec. 3. It is divided into two separate sections, the first one (3.2.1) on rare earth chelate lasers and the second (3.2.2) on aprotic liquid lasers. In the first section (3.2.1) the introduction is followed by the preparation and solution chemistry of rare-earth chelates, cells for liquid lasers, and laser results. The second section (3.2.2) contains an introduction, a discussion of the chemistry of aprotic laser solutions with Nd, a section on laser systems, and an explanation of the apparatus used in connection with the operation of aprotic lasers. The article as a whole contains a great deal of useful information on inorganic liquid lasers.

The fourth section of the handbook is entitled Other Lasers and is divided into a section (4.1.1) on infrared and visible free-electron lasers by Donald Prosnitz, one on millimeter and submillimeter free-electron lasers by V. L. Granatstein, R. K. Parker, and P. A. Sprangle, and a short article on x-ray lasers by Raymond C. Elton. Section 4.1.1 contains a clear explanation of the classification of free-electron lasers, a review of the small-signal gain equations of the Compton free-electron laser, tabulates the free-electron laser small-signal gain equations in Table 4.1.1.4, and presents a summary of free-electron laser experiments (which, in view of the substantial progress made in such experiments in the past year, is not current). Section 4.1.2 is concerned primarily with collective interaction free-electron lasers via stimulated Raman scattering, presents calculations of the Doppler-shifted laser frequency, the growth of the scattered wave, laser efficiency, and considers limitations imposed by electron velocity spread. A final section reviews experiments performed through 1981.

Section 4.2 reviews the considerable progress that has been made towards the demonstration of x-ray lasers. This article is very brief; as few experimental results have been reported to date, the field is still in its infancy.

Section 5.1 on masers, written by Adrian E. Popa, is a good review of the various types of masers (gas beam, optical pumped gas, solid-state) and covers two practical maser designs, one a hydrogen maser oscillator and the other a ruby maser amplifier. Section 5.2 by James M. Moran is entitled Maser Action in Nature, and the reviewer found it to be a splendid and intriguing article which presents the current models of cosmic masers and maser characteristics. The section on maser characteristics discusses molecular species, location, spectra, polarization, time variations, structure, dynamics, and pumping. Section 6 of Volume I covers laser safety and includes a discussion of optical radiation hazards (6.1) by David H. Sliny, electrical hazards from laser power supplies

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TECHNICAL EXHIBIT

An informal exhibit of table-top displays of equipment and materials will be held in conjunction with the meeting. Ample time will be allowed for the attendees to visit the exhibits and exchange information with representatives of companies from all areas of the optical community. Information on the exhibit can be obtained from

Mary Dean VanLandingham, Exhibits Manager
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MEETING INFORMATION

A comprehensive program of short courses, symposia, and technical sessions is planned. For further information contact

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(6.2) by James K. Franks, and hazards from associated agents (6.3) by Robin K. DeVore. Section 6.1 begins with injuries to the eye and skin, considers the risk of exposure, presents a hazard evaluation and laser classification, and gives practical safety measures. Section 6.2 considers the physiological effects of electric current, makes practical safety recommendations, and most important, lists first aid procedures for shock victims. This section of the handbook should be read by everyone working with lasers. The final section (6.3) treats airborne contaminants, contaminant concentrations, the control of chemical hazards, respiratory protective devices, contaminant detection, noise hazards, fire hazards, cryogenic hazards, and radiation hazards.

While the reviewer found that a few of the sections of the handbook were below par, the overall quality is very high, and the book will undoubtedly be widely used by laser and optics researchers and engineers for many years to come. It is timely and contains a wealth of useful information. The editor and advisory board are to be congratulated for producing a very useful and worthwhile volume on laser technology.

Lasers: Selected Reprints

Donald C. O'Shea and Donald C. Peckham, Eds., 139 pp., illus., references. Code No. RB-36. American Association of Physics Teachers, Publications Dept., Graduate Physics Bldg., State University of New York, Stony Brook, NY 11794 (1982) $4.00.

Reviewed by Richard E. Grojean, Northeastern University, Dept. of Electrical and Computer Engineering, Boston, MA 02115.

This book, as the name indicates, is a collection of 35 reprints of articles that touch on many aspects of lasers, from theory and description of operation to exploitation of the coherence of laser radiation for the demonstration of other optical phenomena. Of the 35 reprints two are resource letters, six provide historical background, 26 are devoted to equipment, demonstrations, and experiments, and one is concerned with laser safety.

The editors do not provide any indication as to their purpose in selecting these particular reprints or to the readership for whom the collection is intended. We may assume, since the collection is published by the AAPT, that the intended readership is that part of the academic community which has an interest in lasers but is not intimately familiar with their theory or use. The two resource letters provide an excellent and convenient reference to the literature for readers who wish to broaden their knowledge of lasers and laser applications.

The background required to read and understand the remaining 33 articles in the collection varies widely. Of the six reprints providing an historical background and perspective, two are quite theoretical and require a knowledge of the quantum and statistical nature of radiation. The remaining four are quantitative and/or descriptive. The majority of the 26 reprints that describe experiments and demonstrations suitable for the elementary lab or classroom can be appreciated and understood with only a basic background in geometric and wave optics.

The equipment described ranges from such simple devices as photocell photometers and pinhole spatial filters to ultrasonic and mechanical modulators for communications applications and signal analysis. The demonstrations and experiments involve direct measurements of laser mode structures and various applications which exploit the coherence properties of laser radiation to demonstrate interference and diffraction phenomena, metrology, and holography. Last, but certainly not least, is an article on laser safety in the laboratory.

The choice of articles to be included in a selection of reprints is, of course, a matter of personal preference. It is difficult to judge in this case how successful the editors have been in achieving their goal since the goal is unstated. However, this collection does provide a rather well-balanced set of papers on many of the varied aspects of lasers and the applications of laser radiation. The selection of background papers reflects those authors whose names are intimately associated with the development of the device (Einstein, Schawlow, Townes, and others). The two resource letters alone provide a well-organized and convenient avenue to the literature.

If any criticism is in order (again, this comment reflects personal preference), it is only that it would be nice to have some references to transistor lasers. Also, more emphasis could be placed on laser safety by moving the reprint from the end to the beginning of the collection.

Light Transmission Optics, Second Ed., Van Nostrand Reinhold Electrical/ Computer Science and Engineering Series

Dietrich Marcuse, 560 pp., illus., index, references. ISBN 0-442-26309-0. Van Nostrand Reinhold Company, Inc., 135 West 50th St., New York, NY 10020 (1982) $32.50.

Reviewed by C. M. Verber, Battelle Columbus Laboratories, 505 King Ave., Columbus, OH 43201.

This is the second edition of what has almost become a classic text on guided wave optics. It contains, intact, all of the original 1972 edition plus a section on the Gaussian approximation of the fundamental waveguide mode and two new chapters, "Theory of Multimode Fibers" and "Dispersion in Fibers."

Marcuse's style is characterized by careful attention both to mathematical development of the subject material and to discussions aimed at developing the reader's intuitive appreciation of the mathematical results. This combination of features more than makes up for the fact that some of the subjects (e.g., gas lenses) are no longer of current interest and that there is, in general, a paucity of discussion of specific devices to flesh out the excellent general development of the subject.

Two chapters of particular interest in the first edition are "Light Propagation in Square Law Media," which provides a background for understanding GRIN lenses and graded-index fibers, and the discussion of "Coupling Between Dielectric Waveguides," which provides a background for understanding bottle couplers and a wide variety of integrated optical devices.

The two chapters that are new to the second edition are written with the same clarity that characterizes the original edition. In the first of these, the ray equation is developed, trajectories in a variety of index profiles are discussed, and the WKB method is developed and applied to multimode fibers.

The final chapter is devoted to a discussion of dispersion in both single-mode and multimode fibers, much of which is taken from previous publications by the author. This chapter contains much more discussion of actual examples involving various specific fibers and fiber defects than do the preceding chapters, and thus serves to illustrate the application of much of the previous material.

Color Science: Concepts and Methods, Quantitative Data and Formulae, Second Edition

Günter Wyszecki and W. S. Stiles, xv +950 pp., illus., indexes, references. ISBN 0471-02106-7. Wiley-Interscience, New York (1982) $75.00.

Reviewed by David L. MacAdam, Institute of Optics, University of Rochester, Rochester, NY 14627.

This book is a compendium of almost all that is known quantitatively about color. It contains all of the recommendations of the International Commission on Illumination (CIE) for use in color measurement. Much of the data are not available in any other book.

Most of the book is "directed to the advanced student and research worker in color—physicist, psychologist, and physiologist." The material is "presented in considerable detail so as to make the book as much as possible a unique source of reference material for the research worker and serious student of color science. Trichromatic principles and their application loom large."

The eight chapters are entitled 1) Physical Data, 2) The Eye, 3) Colorimetry, 4) Photometry, 5) Visual Equivalence and Color Matching, 6) Uniform Color Scales, 7) Visual Thresholds, 8) Theories and Models of Color Vision. They are followed by a 195 page Appendix of Extended Tables and Illustrations. A 40 page list of references, a very useful 10 page Author Index that lists all of the pages on which each author's contributions are discussed, and a 15 page subject index complete the 950 page book.

Most of the material on the eye, photometry, classification of matching procedures, Maxwell's method, chromatic adaptation, visual thresholds, and line elements is preparatory for discussions of issues that arise in theories and models of color vision.

Because of space limitations, I will comment only on issues in which I am concerned and will refer only to publications listed in the book.

The sentence that begins at the bottom of p. 9, "There do not seem to occur in nature any other (metameric) spectral radiant power distributions of daylight and identical chromaticity . . .," is not consistent with the results of the research reported by Judd et al. (1964) which required at least four characteristic vectors to account for the observational data. The CIE method of computing daylight spectral distributions, to which the sentence refers, uses only two of the characteristic vectors (pp. 145–147).

Page 164 says that the selected-ordinate method is usually inferior to the weighted-ordinate method. When equally accurate spectrophotometric data are used, propagation of random errors of spectrophotometric data has the effect that, for equal numbers of weighted and selected ordinates, the standard error of X (for the 1931 CIE observer and illuminant C) is 1.55 times as great when the weighted-ordinate method is used as when the selected-ordinate method is used. For Y, that ratio is 1.65, and for Z it is 2.27. For Z, the reason is obvious. When 31 ordinates are used (at 10 nm intervals), the effects of 14 of them in reducing the standard error of Z are wasted by multiplying them by weights that are less than 0.1% of the maximum weights. More than half of the total weight is applied to only three of the weighted ordinates. The selected-ordinate method uses 16 spectrophotometric data within the wavelength range of those three weighted ordinates. The cases of X and Y are similar. Random spectrophotometric errors are better averaged out by the selected-ordinate method because spectrophotometric data are used only where needed.

The color solid indicated by the line drawing in Fig. 5 (3.7) on p. 184 was first published by MacAdam (1935b). Rösch, to whom it is attributed in the legend, did not publish a color solid based on the x,y chromaticity diagram. The color solid he published was based on a color triangle suggested by H. E. Ives in 1915. MacAdam (1935a) was first in the American literature to call attention to the Rösch (1929) paper. The page number (143) given for Rösch, on p. 913 of the book, should be 73.

On p. 306, line 25 refers to a set of red, green, and blue primaries. There were no such primaries. The colorimeter used by MacAdam and PGN produced each stimulus by combination of the light from *two* filters selected from a set of 105 filters whose chromaticities were distributed throughout the chromaticity diagram. The pair was different for each fixed stimulus and for each different direction of deviation from the fixed stimulus. The same filters were used to produce both the fixed and variable stimuli, in each experiment.

The diagram designed by Farnsworth (1958) shown in Fig. 4 (5.4.1) and discussed on p. 310 is not defined numerically or algebraically, so it cannot be used for color-difference computations or any other work for which a uniform-chromaticity-scale diagram is needed.

Pages 430 and 435 say that MacAdam (1956) used monocular matching. He used binocular observations, with the binocular colorimeter described on p. 478.

Page 430 says, "It is questionable whether a pre-exposed adapting stimulus applied to one half (retinal area 0) has a negligible effect on the condition of the juxtaposed half." Von Kries, who first used the method of local adaptation, refuted that objection in 1878 (MacAdam, 1970, p. 102). Whether or not adaptation of one half of the field influences colors perceived in the other, under conditions of adaptation for which daylight and tungsten light appear exactly matched, the reported corresponding colors have identical appearance.

Page 574 expresses doubt that precision of color matching is related in a simple way to just-noticeable color differences. Wright (1941) wrote, "... the ideal method would be to make a large number of matches at each point in the color chart and then to analyse the spread of the observations."

On p. 575, Fig. 4 (7.10.3) shows a nonelliptical locus of just-noticeable differences from white. The first ellipse ever shown on a chromaticity diagram was published by Martin, Warburton, and Morgan (1933). They wrote (p. 34), "The points representing the least perceptible steps from white towards the spectral colors ... lie symmetrically with regard to the white point. The whole of the points lie on an ellipse with white at the center." Martin et al. mentioned determination of mean difference of match from the mean as a possible method of determination, but considered it too laborious. König and Dieterici used that method in their determination of noticeabilities of wavelength differences in the spectrum.

Page 582 falsely attributes to MacAdam (1970) a misquotation of Young's original statement of his three-color theory; "modulation(s)" in lines 9 and 13 were and should be "undulation(s)." Young's revision of that statement, published later in 1802, " substituting red, green, and violet for red, yellow, and blue," is attributed to Helmholtz (1896).

Page 653 asserts that "a green primary stimulus is as effective as a 'white' stimulus in producing additional redness." This is based on a report by Ingling et al. (1978) that "to cancel the perceived redness" of violet spectrum light (e.g., 420 nm) about 30 times more trolands of spectrum green (520 nm) are needed than are needed of spectrum red (680 nm) in combination with nonreddish blue (480 nm) to produce a mixture that has the same retinal illuminance and hue as the violet. Mention of "white" is a digression stimulated by the suggestion of Ingling et al. that their result is related to the Abney effect, in which desaturation of violet by white shifts hue towards red. The idea that green produces redness is the essence of a theory devised by Ingling et al. (1978) to account for their results. Such results can be deduced from any plausible color-matching data. They follow from the fact (MacAdam, 1938) that the mass per lumen (for use with Newton's center-of-gravity principle), which is inversely proportional to the CIE y chromaticity coordinate, is from 10 to 55 times as great for wavelengths less than 450 nm as it is for wavelengths longer than 490 nm. To match the hue of 480 nm (nonreddish blue), 40 lumens of 520 nm must be combined with 1 lumen of 420 nm, whereas to produce 1 lumen of a color that has the same hue as 420 nm requires only 1/3 of a lumen of 680 nm, combined with 2/3 of a lumen of 480 nm. Therefore, colorimetry shows that 120 times as many lumens of 520 nm (green) must be used to "cancel the perceived redness" of 420 nm violet as are needed of 680 nm (red) in combination with 480 nm (nonreddish blue) to produce a color that has the same luminance and hue (redness) as the same amount of 420 nm (violet). Ingling et al. "normalized" the "amounts" of their "primaries" so that equal amounts "cancel" each other. It is easy to calculate that 60 trolands of 680 nm "cancel" the hue of 100 trolands of 520 nm, i.e., form with 520 nm a yellow of the same hue as 580 nm, which Ingling et al. report is neither reddish nor greenish. Consequently, colorimetry predicts that $0.6 \times 120 = 72$ times as many Ingling units of 520 nm (green) as are needed to "cancel" the redness of 1 lumen of 420 nm (violet) as are needed of 680 nm (red) in combination with 480 nm (nonreddish blue) to produce 1 lumen of a color that has the same hue (redness) as 420 nm.

No special theory is needed to account for the results reported by Ingling et al. (1978). Such results follow directly from color-matching curves, alone. They would be practically the same if any recent modifications of the CIE 1931 color-matching data were used instead. Rather than devoting more than two pages to Ingling's *ad hoc* theory, the authors of the book might better, as promised in their Preface, have "refrained from delving too deeply into highly speculative issues of color-vision modeling."

Page 677 implies that empirical line elements, "such as those of MacAdam," make assumptions about visual-response mechanisms. This incorrect implication could be avoided by deleting the first words "insofar as," and replacing "correctly" with "which purportedly."

Despite these and other matters of substance and style for which I have not sufficient space, I heartily recommend this book for careful and discriminating study.

Short Courses

Univ. of Michigan summer conferences

Robotics: Concepts, Theory and Applications (Course#8319), Ann Arbor, MI, Aug. 1-5, 1983. Covers concepts and mathematics of computer-based robots. Topics include kinematics, dynamics and control, robotic lesion, integration of sensor systems, economic justification, and applications. Lectures and laboratory sessions. Chairman: C. S. George Lee. Fee: $750. Engineering Summer Conferences, The University of Michigan, 200 Chrysler Center, North Campus, Ann Arbor MI 48109. 313/764-8490.

Laser Institute of America short courses

Laser Design and Beam Control, New Orleans, LA, Aug. 8-12, 1983. A blend of theory and practice culminating in an actual step-by-step design of a 50 W CO_2 cw laser. Fee: $700. **Acousto-Optic, Electro-Optic, and Guided Wave Devices, Huntsville, AL, Aug. 8-11, 1983.** A practical course covering the principles of operation of acousto-optic, electro-optic, and guided wave devices. Fee: $625. **Laser Safety: Hazard, Inspection, & Control, Cincinnati, OH, Sept. 12-16, 1983.** Provides up-to-date information on federal, state, and international laser safety regulations. Fee: $700. **Fundamentals and Applications of Lasers, Denver, CO, Sept. 19-23, 1983.** A practical course explaining the fundamental operating principles of lasers and their employment in several applications. Fee: $700. Contact Education Director, Laser Institute of America, 5151 Monroe St., Toledo OH 43623. 419/882-8706.

Engineering Technology, Inc. short courses

Laser Fundamentals and Systems, Toronto, Canada, Aug. 8-12 and Anaheim, CA, Oct. 17-21, 1983. Basic elements of a laser, power and wavelength measurements, optical amplifiers and gain, three and four level lasers, optical cavity and mode structure, characteristics of laser mirrors, optical cleaning methods, laser calculation workshops, analysis of seven specific lasers and survey of commercial laser systems. Cost: $700. CEUs: three. **Use of Industrial Lasers in Welding and Surface Treatment Applications, Orlando, FL, Aug. 17-19, 1983.** Features include problem solving workshops and evening operational clinics in local laser development and production facilities where corporate product engineers will demonstrate the use of industrial lasers in laser-induced welding and surface transformation applications,