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# Compact dual-view endoscope without field obscuration

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**Abstract.** We have developed a compact dual-view endoscopic probe without field obscuration to address the need of simultaneously observing forward and backward fields of view (FOVs) in the colon. The objective is compact with the forward-view and rear-view optical paths sharing the same optical elements. The compact objective is new in that no FOV is blocked. The illumination for forward-view imaging is provided by the cylindrical light guide and backward illumination is achieved with a reflector. We have designed, prototyped, and tested the endoscope by comparing it to a standard clinical colonoscope. We will discuss the system concept, objective design, fabrication of the freeform lens, and test results. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JBO.20.7.076007]

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## 1 Introduction

Colorectal cancer is the second leading cause of cancer death in the United States, and it was estimated that ~137,000 individuals would succumb to this disease in 2014, with 50,000 deaths.<sup>1</sup> Colonoscopy is the preferred method to detect and remove precancerous polyps and was performed 11.5 million (M) times in 2009; it was estimated to have exceeded 14M in 2014 at a cost of ~24 billion.<sup>2</sup> The number of colonoscopies is projected to increase as the population ages.<sup>3</sup> Colonoscopy and polypectomy can prevent colon cancer by ~80%, but the benefit appears to be mostly in the distal colon.<sup>4</sup> Most disconcerting are the interval cancers that present within three years of a clearing (polyps detected are removed) colonoscopy with devastating consequences for the patient and physician.<sup>5</sup> The procedure is far from perfect as tandem colonoscopies have demonstrated that it can miss up to 24% of adenomatous polyps, and virtual computed tomography (CT) colonoscopy has shown that it misses 12 to 17% of polyps >1 cm.<sup>6</sup> A typical colon is ~1.6 m long, with ~50 haustral folds and rectal valves that can hide polyps behind them. Without bending the tip, a standard colonoscope with a 140 deg angle of view may fail to image ~20% of the surface area of the colon. Bending the tip of the colonoscope to look sideways improves polyp detection, but still fails to view much of the surface behind folds.<sup>7</sup> Retroflexion of the tip of the scope can be performed in locations such as the ascending colon to look behind folds, but is often not technically possible or can be painful. About two thirds of the polyps missed by standard colonoscopy were reported to be hidden from view by haustral folds.<sup>8</sup> In addition, parts of the colon remain unseen due to sharp angulations.<sup>9</sup> Colon cancer prevention thus hangs precariously on a suboptimal procedure that does not view the total surface of the colon

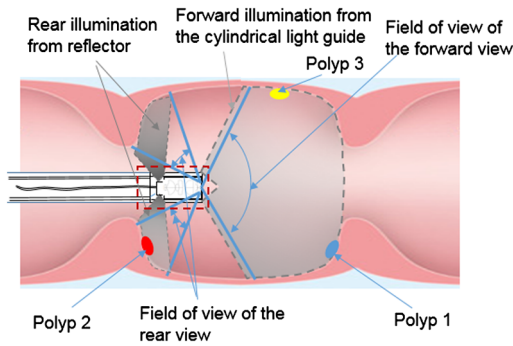
and can fail to detect lesions with low color contrast.<sup>8</sup> A device that maximizes the area of the colon viewed and displays polyps with high contrast would lead to fewer missed polyps and prevent more cancers, including interval and proximal (right-sided) cancers. A more complete inspection should pave the way to longer screening and surveillance intervals and substantial reductions in the national expenditure on colonoscopy.

A number of technologies have been developed to improve the screening area for polyp detection during colonoscopy. A colonoscope with a 170 deg field of view (FOV) did not detect more polyps than a standard colonoscope with a 140 deg view.<sup>10</sup> The greater angle of view still did not allow areas behind folds to be seen. Cap fitted colonoscopy has been reported to increase polyp detection by 0.8 adenomas per patient, but other studies reported no difference in polyp detection.<sup>11</sup> The Aer-O-Scope is a self-propelling device that provides a 90 deg forward view image as well as a 360 deg side view; however, it reached the cecum in only 83% of patients, compared to cecal intubation rate of ~99% by experienced endoscopists.<sup>12</sup> The Third Eye Retroscope (TER) is a miniature probe that is passed through the biopsy channel of a standard colonoscope and retroflexed to illuminate and deliver a continuous retrograde view of the colon.<sup>13,14</sup> TER has a number of limitations making it incapable of meeting the intended clinical needs, for example, 8 to 10% of both forward and rear views are blocked by the shafts of TER and the colonoscope. TER has been summarily rejected by endoscopists, and in a technical review published by the American Society of Gastrointestinal Endoscopy in 2011, it was concluded that a routine colonoscope, with careful tip deflection, could be equivalent or superior to TER.<sup>15</sup> Recently, a colonoscope has been introduced with two additional cameras to the side to produce three images of the colon (one forward and two lateral views); however, it fails to provide views above

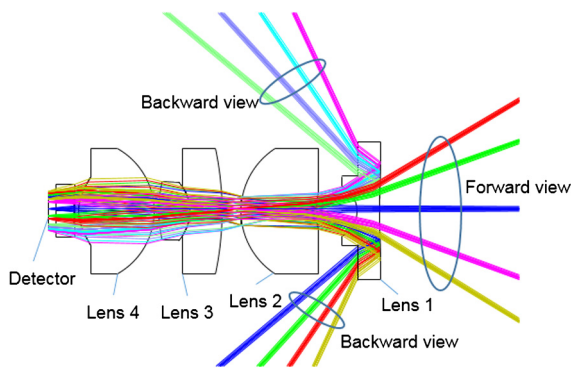
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and below. Furthermore, the system produces three separate video images (one forward and two side-views), and it is difficult for physicians to concentrate on three video images during a long day of endoscopy, which can lead to fatigue and missed polyps.

Currently, no imaging device is able to cover forward and rear views without any obstructed view and which provides a single video image. To address this barrier, we propose to develop a dual-view endoscope combining forward view with omnidirectional backward view so that the physician will be able to examine the colon surface completely without any obstructed view. The forward and rear images can be correlated and registered.



**Fig. 1** Dual-view endoscopy that can illuminate and image both forward and backward fields.



**Fig. 2** Lens configuration of the dual-view objective.

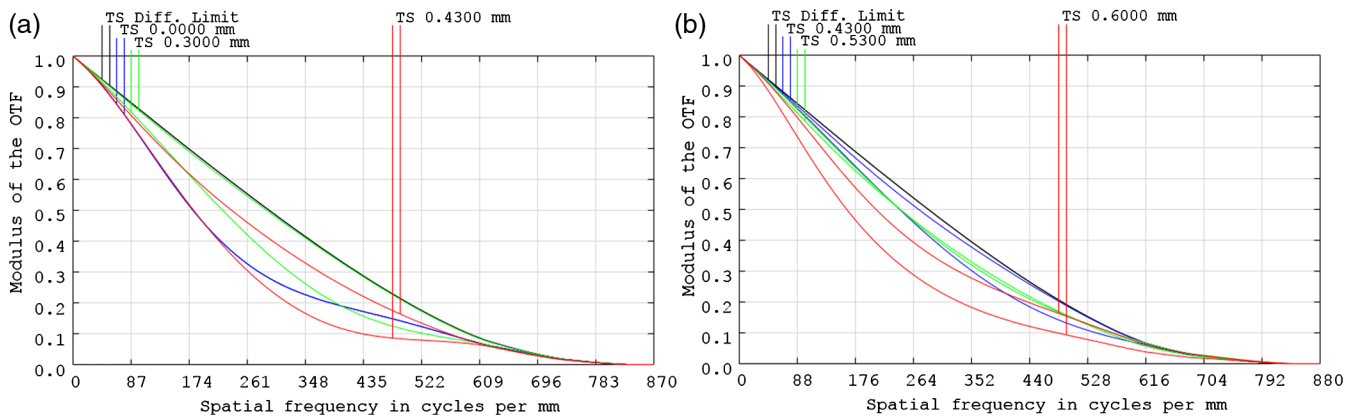
## 2 Dual-View Endoscope

Dual-view endoscopes have been studied by a few research groups.<sup>12,16-18</sup> However, the reported dual-view objectives do not have built-in illumination systems and rely solely on the external illumination of the standard colonoscope. Consequently, both front illumination and rear illumination are partially blocked by the objective. In addition, the rear view is partially blocked by the mechanical lens holder for the front lens group of forward imaging. The novelty of our proposed endoscope is that it can illuminate and image the colon in forward and omnidirectional backward directions without any obstructed view, allowing areas of the colon that are hidden from view to be easily seen by the endoscopist. As shown in Fig. 1, the forward imaging is able to see polyp 1 (in blue) on the fold facing the endoscope, but cannot detect polyp 2 (in red) behind the fold. With backward illumination and imaging, polyps hidden behind folds will be easily seen. Both forward and backward imaging modes are able to capture polyp 3 (in yellow) between folds.

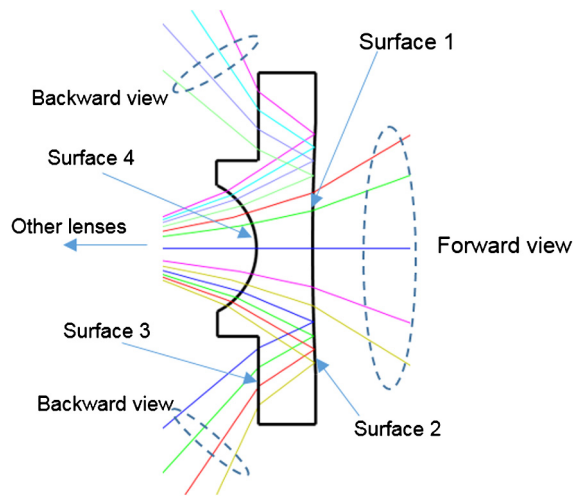
As shown in Fig. 2, the forward and backward views share the same lens components. FOVs for forward and backward views are  $\pm 45$  and 40 deg (from 110 to 150 deg); F/# is 2.4, the same for both views. In this design, the aspherical lenses 1 and 4 are made from polymethyl methacrylate (PMMA), and lenses 2 and 3 are made from glass. Figures 3(a) and 3(b) are their modulation transfer functions, showing both views have diffraction limit performance.

In contrast to other dual-view objective configurations, only one freeform lens is used to combine the forward and backward views in our design. Figure 4 shows the details of the first lens, which consists of four optical surfaces. The light from the forward view enters the objective through surface 1 first and then surface 4; the light from the backward view passes surface 3 and then reflects from surface 2 to surface 4. The light from both views then passes through the rest of the lenses to the detector. The key advantage of this configuration is that the objective is much more compact than other dual-view endoscopic objectives. The challenge in designing this lens is to make sure that both FOVs have good performance. In order to achieve this goal, surface 1 and surface 2 have different radii and surface 2 is aluminum coated. To minimize the aberration for each field, surface 1 and surface 2 can be aspherical.

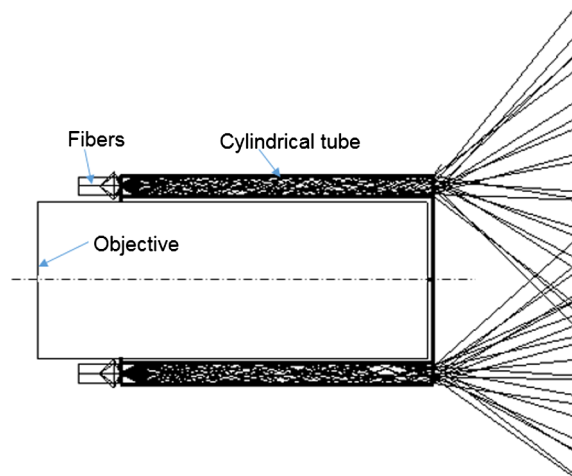
Another challenge in developing the proposed dual-view endoscope is how to fabricate lens 1 with freeform surfaces. While glass material is better to achieve aberration correction because of the higher refractive index, PMMA is used in this



**Fig. 3** Modulation transfer functions of (a) forward view and (b) backward view.



**Fig. 4** Lens 1 details. The front surface has two separated regions (surface 1 and surface 2).



**Fig. 5** Configuration for forward illumination.

prototype because it can be fabricated by single point diamond turning machine. To fabricate lens 1, surface 2 is fabricated first. After surface 2 is aluminum coated, surface 1, surface 3, and surface 4 are fabricated sequentially. The lens is then coated with antireflection coating.

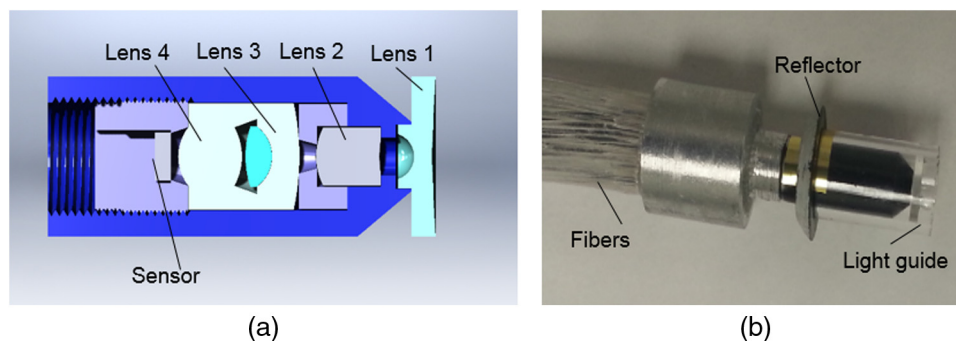
Another challenge in developing a dual-view endoscope is the illumination for both FOVs. Current dual-view endoscopes

either use an external illumination system or place light-emitting diodes (LEDs) in front of the first lens. With LEDs in front of the first lens, the key issue is that the objective cannot be minimized due to the physical size of the LEDs. In addition, the electric wires for LEDs block a small portion of the backward view. Heat generated by LEDs is a problem as well, and in order to address this issue, we use a cylindrical tube to guide the light from the fibers to the front end of the endoscope, as shown in Fig. 5. This cylindrical tube not only guides the light from the fibers to the front end, but also homogenizes the light distribution from the fibers. Instead of the flat surface, the output end of this cylindrical tube can be optimized to achieve wide-angle and uniform illumination. The backward illumination can be directly provided by the fibers or with a reflector as shown in Fig. 6.

### 3 Prototype and System Performance

We have built the prototype and evaluated the performance of this dual-view endoscope. Figure 6 shows the mechanical layout and the prototype of the dual-view objective lens. As the first prototype of this dual-view objective, we purposely designed a 6-mm-diameter objective to ensure we can fabricate the first lens in house. The diameter is 8 mm with a 1-mm-thick cylindrical tube. Figure 7 shows the unprocessed image of a tube with a printed 1951 U.S. Air Force resolution target captured by the prototype probe. It demonstrates that the prototype can simultaneously obtain both FOVs without any obstruction. The rear-view image in Fig. 7 is a mirror image, which we will correct digitally during subsequent development.

We have performed preliminary testing in a colon trainer (Chamberlain Group, Gt. Barrington, Massachusetts). A total of 31 dark red spheres, hemispheres, and discs (to represent polyps and flat lesions) were glued to the inner surface by making incisions into the colon, which were later sealed with glue. Approximately half of the simulated lesions were located in easily visible areas between folds, whereas the rest were placed in difficult to see locations behind folds. A gastroenterology research fellow advanced a standard colonoscope (Fujinon EC530-HL, Fujifilm, Wayne, New Jersey) with a 140 deg forward view to the sealed end of the colon. The image was displayed on a standard endoscopy display monitor. Each endoscopist (two attending gastroenterologists, two fellows) examined the colon trainer with the room lights darkened. Polyps detected were called out by the endoscopist and recorded by the research fellow. The dual-view probe was subsequently attached to the tip of the colonoscope and the withdrawals were repeated by each endoscopist ~14 days later (so that location of polyps could not be recalled) using the dual-view probe's



**Fig. 6** (a) Mechanical layout and (b) prototype of dual-view objective lens.



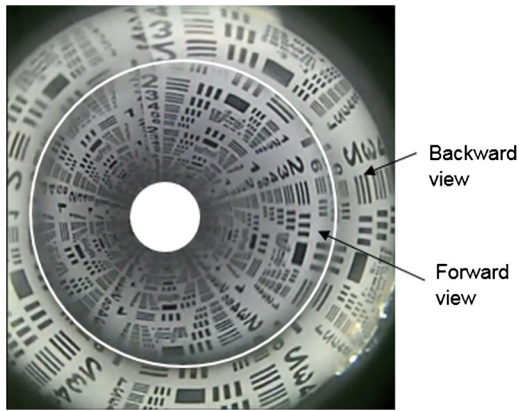


Fig. 7 Image of the cylindrical tube with printed resolution target.

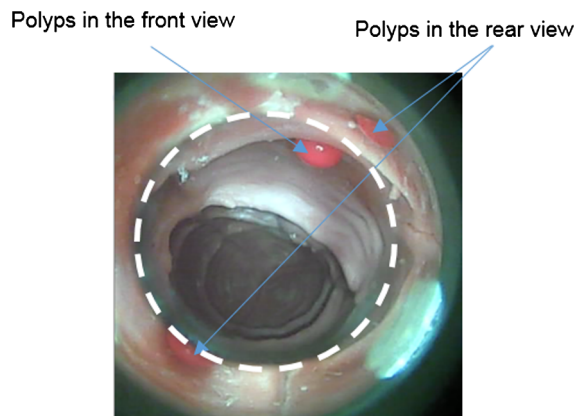


Fig. 8 Images of colon trainer with simulated polyps placed in different locations. The white spots are defects from the lens-assembling process.

own light source and the image display (the standard colonoscope's light and imaging were switched off). Figure 8 shows image obtained with the dual-view probe (the inner circle is comparable to the FOV through a standard forward-view colonoscope). It clearly shows that the dual-view endoscope can detect polyps in front of the fold and behind the fold in the same image. Out of a total of 32 lesions, a mean of  $18.8 \pm 2.1$  lesions were visualized using standard forward-viewing colonoscope, whereas  $28.8 \pm 1.8$  (an increase of 53%) were detected with the dual-view probe ( $p < 0.009$ ,  $t$ -test). This study demonstrates that the proposed dual-view endoscope has the great potential to detect more polyps than conventional large-angle colonoscope.

#### 4 Conclusion

In this paper, we have demonstrated a dual-view endoscope that can simultaneously image forward and backward views. This dual-view endoscope is much more compact than other dual-view endoscopes and has its own forward illumination. The

objective can be minimized to  $<3$  mm so that it can be used as an accessory through the biopsy channel of the standard colonoscope.

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Biographies for the authors are not available.