Dual view capsule endoscopic lens design

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Abstract: A dual view capsule endoscopic (DVCE) lens is proposed with front view and back view functions. This is a hybrid lens with a catadioptric mirror and an aspherical surface to support both view functions. The field of view (FOV) for the front view function is 90 degrees. The FOV for the back view function is 260 to 290 degrees. The TV distortion for the front view and back view function is under 30% and 25%. The corner relative illuminations for the two view functions are above 0.53. The Modulation Transfer Function (MTF) performance at the Nyquist Frequency for the two view functions can be kept above 0.35, even under tolerance they can remain above 0.2. Moreover, the telecentric conditions at the image plane of the DVCE system can support constant magnification through focusing. This condition can reduce the measurement error by slightly defocusing of the lens. Thus, the two view functions can offer physicians a wide viewing angle to deal with lesions over the fold.

OCIS codes: (080.3620) Lens system design; (080.2740) Geometric optical design; (080.3630) Lenses.

References and Links

1. American Society for Gastrointestinal Endoscopy, "Appropriate Use of Gastrointestinal Endoscopy," Gastrointest. Endosc. **52**(6), 831–837 (2000).
2. G. M. Cobrin, R. H. Pittman, and B. S. Lewis, "Increased diagnostic yield of small bowel tumors with capsule endoscopy," Cancer **107**(1), 22–27 (2006).
3. M. Ou-Yang, S. W. Huang, Y. L. Chen, H. H. Lee, and P. K. Weng, "Design of wide-angle lenses for wireless capsule endoscopes," Opt. Eng. **46**(10), 103002 (2007).
4. Olympus," http://www.olympusamerica.com/cpg_section/cpg_PressDetails.asp?pressNo=549.
5. Givenimage," http://www.givenimaging.com/en-us/Innovative-Solutions/Capsule-Endoscopy/Pillcam-SB.
6. M. Ou-Yang and W.-D. Jeng, "Design and analysis of radial imaging capsule endoscope (RICE) system," Opt. Express **19**(5), 4369–4383 (2011).
7. J. Pohl, M. Delvaux, C. Ell, G. Gay, A. May, C. J. Mulder, M. Pennazio, E. Perez-Cuadrado, and P. Vilmann, ESGE Clinical Guidelines Committee, "European Society of Gastrointestinal Endoscopy (ESGE) Guidelines: flexible enteroscopy for diagnosis and treatment of small-bowel diseases," Endoscopy **40**(7), 609–618 (2008).
8. S. Itoh, S. Kawahito, and S. Terakawa, "A 2.6mW 2fps QVGA CMOS One-Chip Wireless Camera with Digital Image Transmission Function for Capsule Endoscopes," Proc. IEEE ISCAS (2006).
9. W. J. Smith, "Reversed telephoto lenses," in *Modern Lens Design Second Edition*, (Mc-Graw Hill), 403–404 (2005).
10. L. J. Lu, X. Y. Hu, and C. Y. Sheng, "Optimization method for ultra-wide-angle and panoramic optical systems," Appl. Opt. **51**(17), 3776–3786 (2012).
11. G. I. Kweon, K. T. Kim, G. H. Kim, and H. S. Kim, "Folded catadioptric panoramic lens with an equidistance projection scheme," Appl. Opt. **44**(14), 2759–2767 (2005).
12. J. Zeng, X. Su, and G. Jin, "Incorporating lens distortion into the design of undistorted catadioptric omnidirectional cameras," Appl. Opt. **45**(30), 7778–7784 (2006).

#231475 - $15.00 USD Received 5 Jan 2015; revised 27 Feb 2015; accepted 10 Mar 2015; published 26 Mar 2015

13. W. J. Smith, "Stops, apertures, pupils and diffraction," in *Modern Optical Engineering Fourth Edition*, (Mc-Graw Hill), 182–185 (2008).
14. W. J. Smith, "Reversed Telephoto Retrofocus and Fish-Eye lens," in *Modern Lens Design Second Edition*, (Mc-Graw Hill), 395–431 (2005).
15. W. J. Smith, "Stops, apertures, pupils and diffraction," in *Modern Optical Engineering Fourth Edition*, (Mc-Graw Hill), 182–183 (2008).
16. L. J. Lu, X. Y. Hu, and C. Y. Sheng, "Optimization method for ultra-wide-angle and panoramic optical systems," Appl. Opt. **51**(17), 3776–3786 (2012).
17. J. W. Pan, "Compact camera module testing equipment with a conversion lens," Opt. Express **20**(5), 5303–5312 (2012).
18. W. J. Smith, Reversed telephoto (Retrofocus and Fish-Eye) lenses," in *Modern Lens Design Second Edition*, (Mc-Graw Hill), 395–431 (2005).
19. K. Gyeong-Il and L. Milton, "Design of a Mega-pixel Grade Catadioptric Panoramic Lens with the Rectilinear Projection Scheme," J. Opt. Soc. Korea **10**(2), 67–75 (2006).
20. G. I. Kweon, K. T. Kim, G. H. Kim, and H. S. Kim, "Folded catadioptric panoramic lens with an equidistance projection scheme," Appl. Opt. **44**(14), 2759–2767 (2005).
21. R. C. C. Wang, M. J. Deen, D. Armstrong, and Q. Fang, "Development of a catadioptric endoscope objective with forward and side views," J. Biomed. Opt. **16**(6), 066015 (2011).
22. B. Hayashida, "F-theta lens system for four-group construction," U.S. patent 4400063 (Aug 23, 1983)
23. K. Fuse, "F-theta lens," U.S. patent 6324015 (Nov 27, 2001).
24. W. J. Smith, "Stops, the practice of optical engineering," in *Modern Optical Engineering Fourth Edition*, (Mc-Graw Hill), 620–622 (2008).
25. J. W. Pan, S. Y. Chung, J. J. Wang, Y. M. Lin, M. J. Hsu, and I. C. Feng, " Lens system of capsule endoscope with dual-view, " T.W. patent I474040 (Feb 21, 2015).

1. Introduction

The endoscope is a very important tool which can provide doctors direct observation of the digestive tract. Through digestive endoscopy, we can evaluate gastrointestinal bleeding, the mucosal structure, superficial vessel patterns, motility, obstructions, and benign or malignant lesions. Compared with conventional endoscopy, capsule endoscopy is less invasive, easier for endoscopists to perform, and involves fewer complications, such as trauma or rupture of the digestive tract. Conventional endoscopy is contraindicated when patients are not willing to cooperate, but capsule endoscopy is not [1]. Furthermore, for examination of the small intestine, the capsule endoscope provides a safer and more comfortable examination experience to the patient and more complete pictures to the doctors than conventional endoscopy [2].

There are two main types of lens architecture used in the capsule endoscope. One is the front imaging capsule endoscope (FICE) which utilizes a traditional wide angle lens, but there are some disadvantages to this structure, such as the narrow field of view, short depth of focus and discontinuous image. Another type is the radial imaging capsule endoscope (RICE). This capsule endoscope can obtain a continuous image during the checking period, but it still has some disadvantages for endoscopic applications. The main disadvantage is loss of the front view function. In a traditional examination, doctors use the front view to find any malignant or benign lesions. To overcome the limitations of an endoscope with only a front view function and to deal with wrinkled intimae, the capsule endoscope needs new features.

In this study, the goal is to design a capsule endoscope with a front view and wide viewing angle for the examination of wrinkled intimae. A novel capsule endoscope lens with a dual view function is proposed, the dual view capsule endoscopic lens (DVCE lens). The DVCE lens design offers a front view angle and back view angle simultaneously and overcomes the limitations of the traditional lens design with only one view. For the front view function a wide angle telecentric lens is used. For the back view, the lens part consists of a catadioptric mirror and an f-theta lens with a telecentric condition. The key feature of the dual view DVCE lens is supplied by using a hybrid free form lens to obtain the front view by its center part and the back view by its edge part. The front field of view (FOV) of the capsule endoscope can exceed 90 degrees. The back FOV can cover the range from 260 to 290 degrees. For the dual view capsule endoscope system, the MTF value can reach 0.29 at full view for dual view configurations. Moreover, the optical distortion of the front view can be controlled under 80%

and 25% under front view and back view conditions. Given the tolerance analysis, the Modulation Transfer Function (MTF) value at the Nyquist frequency still remains at 0.3. The DVCE lens has been finished and the optical performance has been verified. The novel optical design can enable better medical testing in the near future.

2. Design concept and specifications for a dual view capsule endoscope

2.1 Design concept

In the traditional capsule endoscope design the lens is very compact in size with only one viewing angle for searching for lesions. The lens structure is typically a wide angle lens without telecentric conditions at the image plane [3]. The typical FOV of the capsule endoscope lens is around 80-154 degrees [3–5]. Recently, Ou et al. used a conical mirror as the first optical element in a capsule endoscopic lens to bend the FOV to obtain a side viewing angle [6], the so-called RICE lens. Owing to the conical mirror, the FOV of the capsule endoscopic lens can be increased to 260 to 290 degrees for the side view function. However with the RICE lens, the front viewing angle of the traditional capsule endoscope lens is lost, a disadvantage for doctors in their search for disease. Furthermore, the intestine is not like a clear tunnel but has folds and loops. The RICE lens cannot get a clear image given the intestinal redundancy and looping.

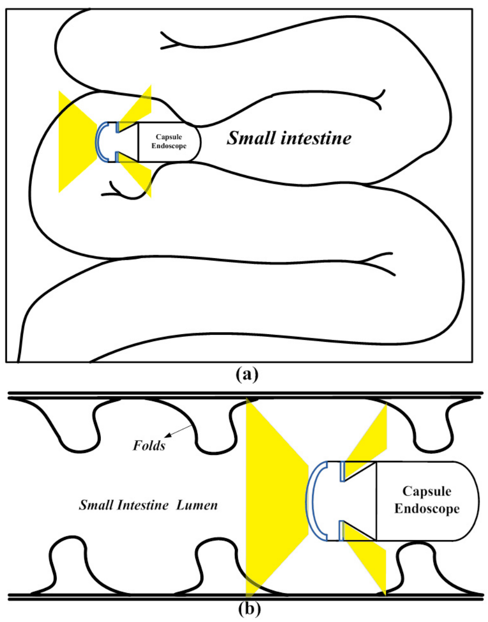

Fig. 1. Dual view capsule endoscope (a) in the small intestine (b) magnified picture.

We strive to combine the advantages of the FICE lens and the RICE lens, by developing an aspherical surface hybrid of the two designs to create the novel DVCE lens design illustrated in Fig. 1. Figure 1(a) shows the DVCE working in the human digestive tract. Figure 1(b) shows the novel DVCE lens design with the simultaneous front and the back functions. In order to improve the image quality and deal with positioning errors caused by some defocusing issues, the telecentric condition at the image plane is adopted in this design. In the rear part of the DVCE lens design, the same lens group is used in the lens architecture for the front and back view configurations. The DVCE lens design allows inspection of the intestinal folds without the reverse function necessary in the conventional checking process [7]. Moreover, in conventional endoscopy, inflation and the associated apparatus are utilized

#231475 - $15.00 USD Received 5 Jan 2015; revised 27 Feb 2015; accepted 10 Mar 2015; published 26 Mar 2015

to make a more detailed observation of lesions over the folds. In capsule endoscopy, it is difficult to overcome the obscuring of the visual field by the intestinal folds. However, the DVCE lens can offer the function of being able to check for lesions over the folds without any assistance. The DVCE can help overcome the disadvantages of conventional capsule endoscopes in terms of the viewing angle.

2.2 Dual view capsule endoscopic lens specifications

For an image capture system, the image sensor is an important element. The specifications for the complementary metal-oxide-semiconductor (CMOS) sensor, used in order to reduce the volume and power consumption of the capsule endoscope system, are shown in Table 1. [8]. This image sensor can work under lower power consumption with a high bit rate.

Table 1. Specification of the CMOS Sensor for the DVCE Lens

Parameters	Specifications
Chip size	4.84(H)mmx4.34(V)mm
Supply Voltage	2V
Array Size	320 um x240 um
Pixel Size	10μm
Carrier Frequency	20MHz
Bit Rate	2.5Mbps
Resolution	320X240(QVGA)
Power consumption	2.6mW

Owing to the dual view conditions, the capsule endoscope uses two effective focal lengths under the same CMOS image sensor. Thus, the CMOS sensor area can be divided into two image zones. One is the front view zone with an image height from 0 mm to 1.1 mm and the other is the back view zone with an image height form 1.4 mm to 2.0 mm. Between 1.1 mm to 1.4 mm is a blind spot without any image. The blind spot can be divided between the front view image and the back view image. For the front view configuration, the DVCE lens should have a typical wide angle field of 90 degrees [9] so the effective focal length of the front view configuration is 0.76 mm. For the back view configuration, the DVCE lens design adopts an ultra-wide-angle lens with a catadioptric mirror [10–12]. The effective focal length (EFL) of the back view configuration for the DVCE is 1.23 mm. The FOV of the back view configuration is 260 to 290 degrees. All optical specification of the DVCE lens design is shown in Table 2.

Table 2. Optical Specifications of the DVCE Lens

	Front view configuration	Back view configuration
F-number	3.5	3.5
Magnification	–0.0501	–0.0642
FOV (field of view)	90 degrees	260 degrees to 290 degrees
Image height	0-1.1mm	1.4mm-2mm
CRA (chief ray angle)	<5 degrees	< 5 degrees
Object distant	9 mm	7 mm
Nyquist frequency	50 lp/mm	50 lp/mm

According to the specifications for the DVCE lens, the entire chief ray angle is less than 5 degrees. There are two main reasons for the near telecentric condition, the first being that a reduction in the cosine law effect which can improve lower relative illumination at the corners or the dark corner issue [13]. The second reason is constant magnification through the focus [13].

3. Optical design and performance analysis

3.1 Optical design and layout of the DVCE lens

The layout of the novel DVCE lens is shown in Fig. 2(a). According to the specifications, there are two configurations for the front and back viewing functions. Each configuration has its own optical features. The descriptions below are also divided into the front and back view configurations.

For the front view configuration of the DVCE lens, the lens structure is a typical wide angle lens with telecentric conditions, as shown in Fig. 2(b). This lens consists of two lens groups (-, +) and is typically the reverse telephoto type [14]. The notation (-, +) refer to the optical power as negative for the first lens group and positive for second lens group . In order to let the lens work at a lower F/# under a wider angle, the first negative group is divided into three lenses. The three lens structures are (-,-, +). In order to keep the Petzval sum lower, the two negative front lenses introduce the undercorrect Petzval sum into the DVCE lens and the single positive rear lens introduce the overcorrect Petzval sum into the DVCE lens. There is some balance achieved for the Petzval sum. The rear lens group is the positive lens group. The lens stop is set at the position between the front negative lens group and rear positive lens group. The lens stop is also at the focal plane of the rear positive lens group [15]. Of the two configurations, the rear lens group after the stop is the common part for the DVCE lens. The lens for the front view configuration is a typical wide angle lens with a telecentric condition. Therefore, the stop is the telecentric stop located at the focal point of the rear lens group [13]

Based on the specifications in Table 1. and the above discussion, we searched the United States Patent database for patent results for the DVCE lens design. Accordingly, US patent 4647161 and US patent 4269478 were used as the starting point for the front view configuration design [16,17]

In this DVEC lens design, the rear lens group is common to both the front and the back view configurations. This lens group is comprised of a typical f-theta lens with telecentric condition at the image side. In order to reduce the petzal curve, the lens group is divided into three positive lenses. In order to obtain a wide angle of view, the front lens group in the front view configuration is a negative lens group. Owing to the wide angle FOV, the astigmatism, coma and other aberrations are much larger. In order to reduce the aberrations, the first surface of the negative lens is aspherical. We try to combine the catadioptric mirror and aspherical front lens group used for the front view configuration into one hybrid lens surface. (4)The outside part of the hybrid surface can be used as the catadioptric mirror after coating it with silver for the back view configuration. Furthermore, the inside part of the hybrid surface is used as the transmissive aspherical surface for the front view configuration.

For the back view configuration of the DVCE lens, the lens structure is a typical catadioptric panoramic lens with a telecentric condition at the image plane [18–21]. The lens structure is shown in Fig. 2(c). This configuration can be divided into two major parts. The first major part is comprised of a catadioptric mirror for the rear view function. The optical power of the catadioptric mirror is negative. The mirror design rules are based on previous research [11,12,18].The second major part is comprised of a telecentrcic f-theta lens with an external stop [22]. For the back view configuration, the stop is between the catadioptric mirror and the rear lens group. The rear lens group is the common part in the DVCE. The lens group is a typical f-theta lens with a telecentric condition [22,23]. Moreover, the catadioptic mirror integrates the least aspherical surface of the front lens group into one aspherical lens. This method makes the entire DVCE lens more compact in size and lower in weight.

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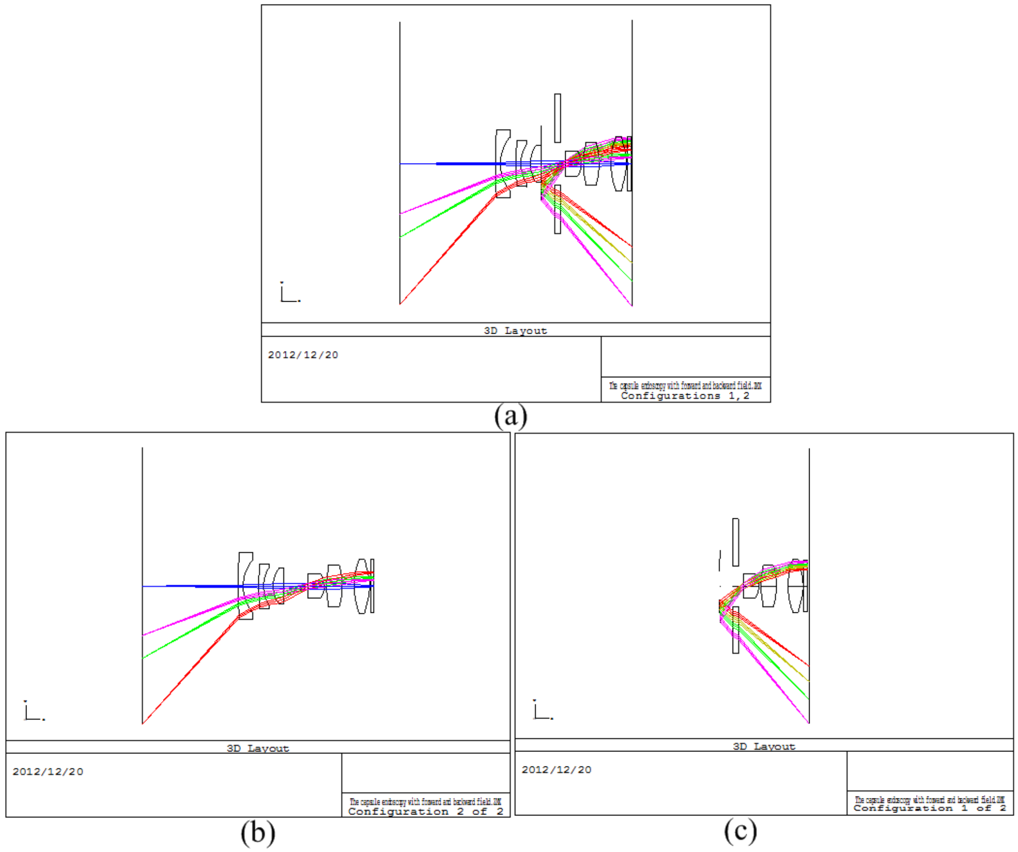

Fig. 2. (a) Conceptual representation of the DVCE lens; (b) front view configuration of the DVCE lens; (c) back view configuration of the DVCE lens.

Based on the specifications in Table 1. and the above discussion, we can use the lens group after the stop with the catadioptric mirror to allow the field of view to exceed 180 degrees for the back view configuration. The catadioptric mirror is used as the front lens part. The catadioptric mirror allows an FOV in excess of 180 degrees. There is serious pupil aberration. In order to allow accurate ray tracing, chief ray aiming is used but a lot of time is required to calculate the optical performance [24].

At the image plane of the DVEC lens, there are two image views on the same CMOS sensor. One is the front view and the other is the back view. In order to help the doctor to avoid making mistakes by confusing the two images, there is a gap between them. The 0.3mm gap is created by the blind spot on the CMOS sensor. With the DVEC lens design, the image height is from 0 to 1.1 mm for the front view configuration and 1.4 to 2 mm for the back view configuration. Forth more, we also need software process to separate the two images and display them on separate monitors. This software process would probably be less confusing and not to force one to waste imaging pixels on the sensor by including a gap.

At this DVCE lens, there are two kind optical materials such as polycarbonate (PC) and COC. In order to reduce the chromatic aberration, we use the polycarbonate (PC) and COC to meet the goal. The refractive index of nd is 1.58 and the Abbe number is 29.9 for PC. The refractive index of nd is 1.53 and the Abbe number is 56.2 for COC. The three optical materials are used at the rear part of DVCE lens.

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3.2 Optical performance of the DVCE lens

3.2.1. Distortion and relative illumination

Optical distortion is inherent with a typical wide angle lens. The optical distortions for the two configurations are shown in Fig. 3. For the front view DVCE lens configuration, the optical layout is a typical reverse telephoto structure so there is serial barrel distortion. According to Fig. 3(a), the optical distortion is around 80% but the TV distortion is around 30%. The back view configuration has a catadioptic wide angle lens optical layout. There is still serial barrel distortion, as shown in Fig. 3(b). Owing to the high precision tooling with symmetry, we use the aspherical surface as a catadioptic mirror. The optical distortion is around 35% to 60%.The TV distortion still reaches 25%.

Moreover, the two configurations for the DVEC lens work under the wide angle lens. The typical wide angle lens inherently possesses lower relative illumination owing to the cosine – fourth-power-rule [14]. However, the image plane for both configurations holds the near telecentric condition to reduce the effect of the cosine-fourth-power-rule. The relative illumination for the two configurations is shown in Figs. 3(c) and 3(d). For the front view configuration, the relative illumination decreases from 1 to 0.61 in the field range from 0 to 1.1 mm as shown in Fig. 3(c). For the back view configuration, the relative illumination of the center field ranges from 0 to 1.4mm is 0. The main reason is that it is obscured by the rear part lens group after passing through the free-form mirror of the DVEC lens. The relative illumination also decreases from 1 to 0.53, as shown in Fig. 3(d). In one word, we control the minimum relative illumination more than 0.5 for no dark corner issue.

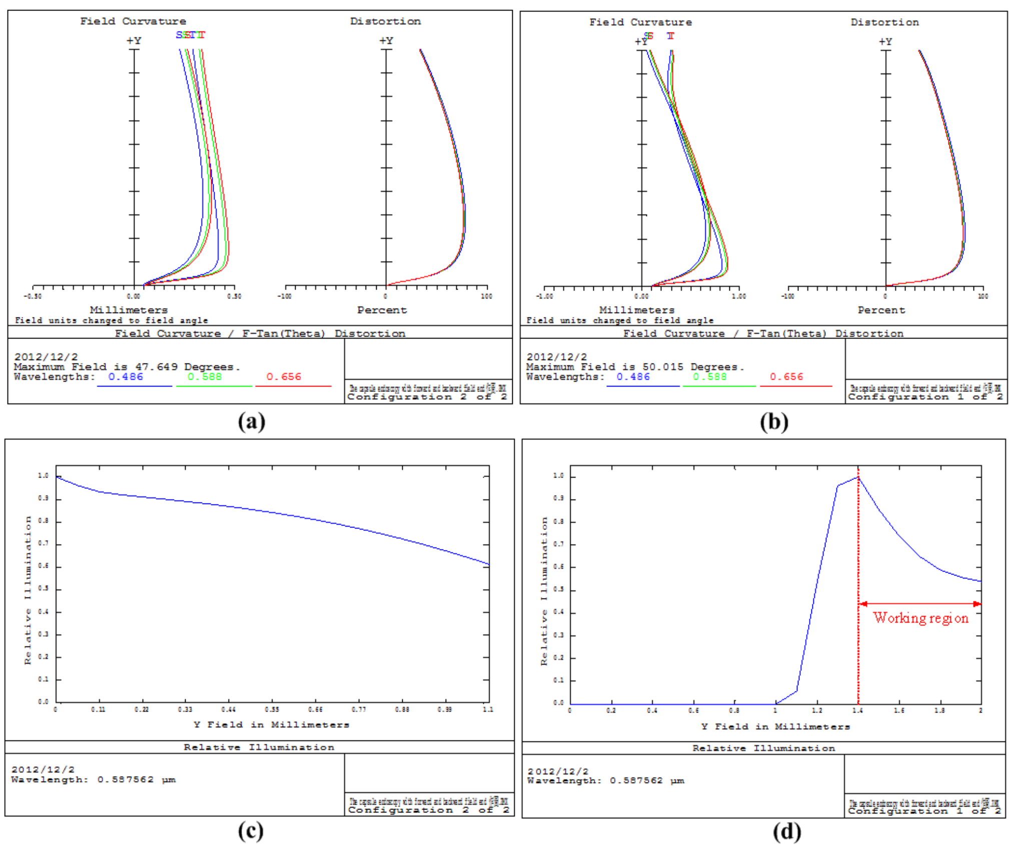

Fig. 3. (a) and (b) Field curvature and distortion (c) and (d) relative illumination for front view configuration and back view configuration of the DVCE lens.

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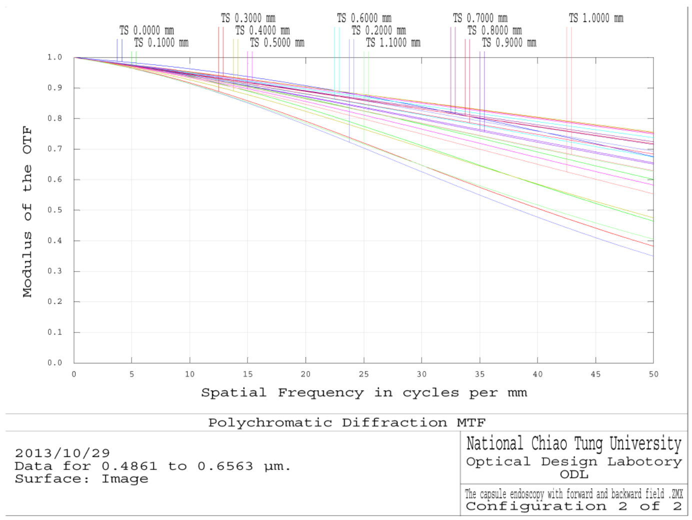
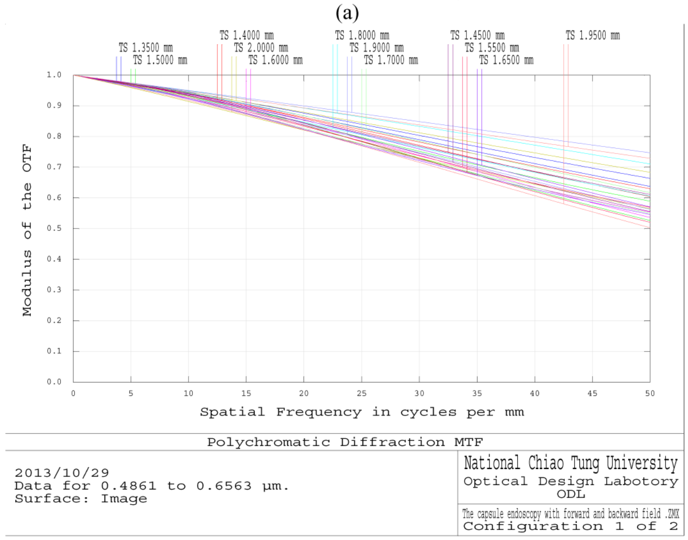
3.2.2. Modulation Transform Function (MTF) of the DVCE lens

In an image system for medical examination, image quality is the most important factor for the detection of lesions. The modulation transform function (MTF) is representative of the image quality in a lens design. The MTF graphs for the DVCE lens are shown in Fig. 4. Owing to the pixel size of the CMOS sensor, the Nyquist frequency is 50 lp/mm. In Fig. 4(a), it can be seen that the MTF values at the Nyquist frequency are larger than 0.35 for all field heights for the front view configurations. In Fig. 4(b), it can be seen that the MTF values at the Nyquist frequency are larger than 0.5 for the field range from 1.4 mm to 2 mm for the back view configurations.



(a)



(b)

Fig. 4. MTF graphs of the DVCE lens for the (a) front view configuration and (b) back view configuration.

4. Tolerance analysis and prototype sample

The last step in the lens design is tolerance analysis. The key for mass production is the precision level of the tolerance data [24]. The precision tolerance data shown in Table 3 are

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used in the tolerance analysis. This is found by utilizing the inverse sensitivity MTF tolerance function in the Zemax software to verify the production ability. The results are shown in Fig. 5. The Tangential MTF tolerance results for two figurations at the large field are shown in Table 3. The cumulative probability MTF result at Nyquist frequency under Monte Carlo analysis is at Table 4. But at the worst case for the two configurations, the MTF remains at 0.22 for all fields as shown in Fig. 5(a). For the back view configuration, the MTF is still worse remaining above 0.20 for all fields, as shown in Fig. 5(b). According to the tolerance performance shown in Table 3, the degree of sensitivity for the front view configuration is higher than that for the back view configuration. Moreover, the most sensitive element is the last DVCE lens. The most critical parameter is the y-decenter for the last lens element in the DVCE lens. Finally, the DVCE lens tolerance is based on the front view configuration tolerance table.

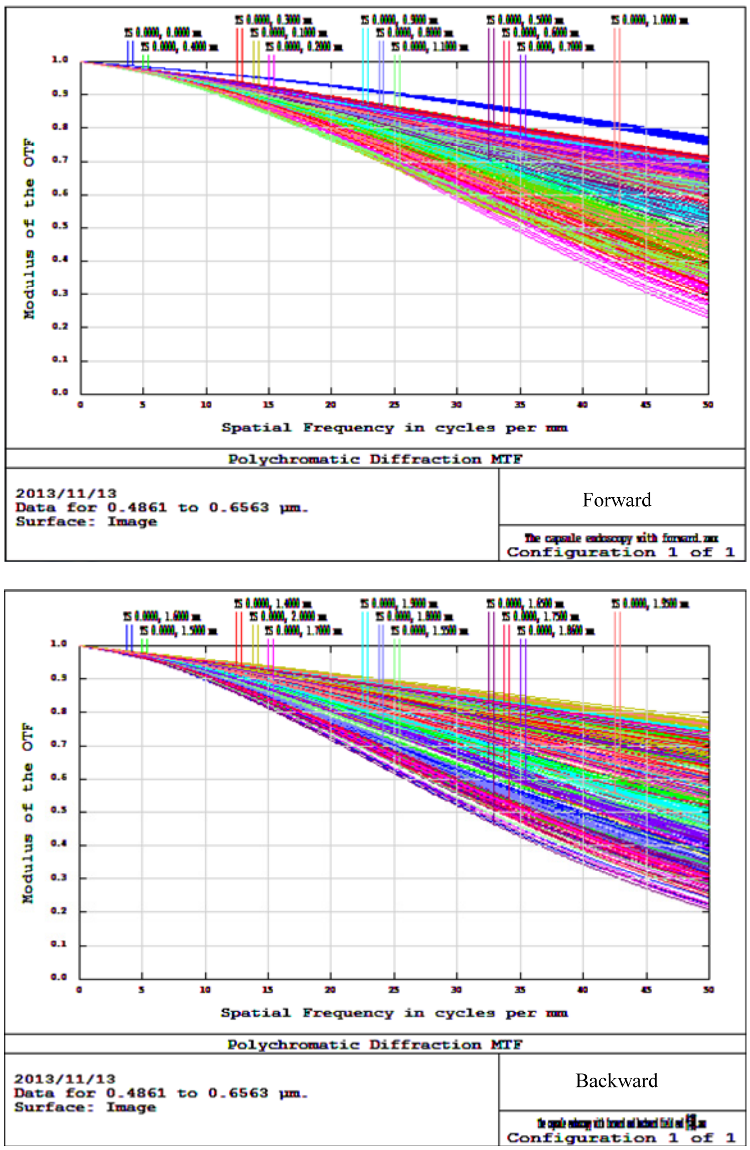

Fig. 5. Overlay MTF graph of the DVCE lens for the (a) front view configuration and (b) back view configuration.

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Table 3. Tabulation of Precision Optical Fabrication Tolerances

Items	Back view configuration	Front view configuration
Surface Quality	80-50	80-50
Diameter (mm)	± 0.02	± 0.02
Deviation (concentricity), (min)	1	1
Thickness (mm)	± 0.02	± 0.02
Radius (Fr)	8	6
Regularity (Fr)	5	3
Linear Dimension (mm)	± 0.05	± 0.03
Angles	± 7'-15'	± 5′-10'
Most critical element	4th element	6th element
Most critical tolerance item	y-decenter	y-decenter

Table 4. Get Large Field for Two Configurations

Cumulative probability	**Tan. MTF value (Back View)**	**Tan. MTF value (Front View)**
90% >	0.341	0.321
80% >	0.373	0.342
50% >	0.402	0.382
20% >	0.436	0.416
10% >	0.496	0.447

Finally we also do the prototype sample for DVCE lens. The mechanical layout is shown at Fig. 6(a). The green space is RF part. The yellow space is the power part. The prototype of DVCE system is also at Fig. 6(b). The length of the DVCE system is 26mm. The diameter of DVCE system is 13mm. The total volume is around 2875 mm^3. We also capture the grid testing chart by the DVCE system as shown at Fig. 6(c). The DVCE lens design data consults Taiwan patent I474040 [25].

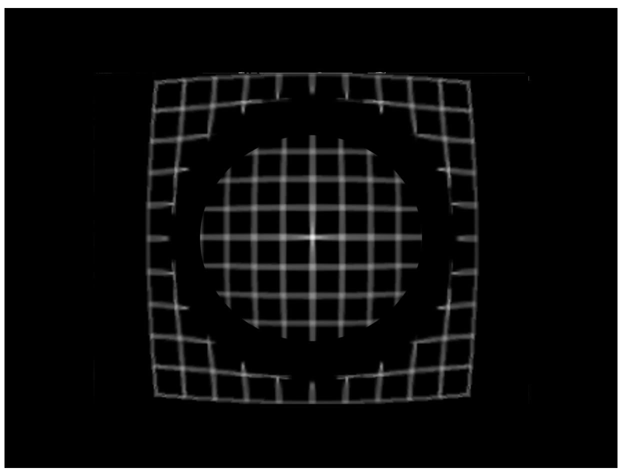

Fig. 6. The mechanical layout (a) and prototype sample (b), testing gird image (c)of DVCE system.

6. Conclusion

In this study, a novel capsule lens with dual view functions is designed using a hybrid lens for two configurations. For the front view configuration, the DVCE lens is a typical wide angle lens with a telecentric condition at the image plane with an FOV that can reach over 90 degrees. The MTF value can remain about 0.29 for all fields. The TV distortion can be controlled to less than 30%. The relative illumination can remain above 0.61 for all fields. For the back view configuration, the FOV can reach 260 degrees to 290 degrees as a consequence

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of the catadioptric mirror. The catadioptric mirror can also reduce pupil aberration due to ultra wide angle lens. The MTF values still remain about 0.35 for all fields. The TV distortion can only be controlled to fewer than 25%. The image quality gets worst under ultra wide angle conditions but to the human eye it is still acceptable. Moreover, the relative illumination can only be maintained at about 0.53 for the maximum field. The relative illumination is still lower in the ultra wide angle condition. A novel illumination system is required by the DVCE lens. Both configurations with tolerance analysis are still finished. The common part for both configurations is the most sensitive and critical part in the DVCE lens. Under these design specifications for the DVCE lens, this design might allow improved detection and evaluation of digestive tract lesions.

Acknowledgments

This study was supported in part by the Chi Mei Medical Center, under project number 103C028, and in part by the Ministry of Science and Technology, under project number MOST103-2220-E-009-009.