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Adaptive lenses based on polarization modulation

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ABSTRACT

We present and demonstrate a technique for producing a high-speed variable focus lens using a fixed birefringent lens and a ferroelectric liquid crystal cell as a polarization switch. A calcite lenses with ordinary and extraordinary focal lengths of 109mm and 88mm respectively, was used to demonstrate focus switching at frequencies of up to 3kHz. Two identical lenses and a single liquid crystal were also used to demonstrate zoom.

INTRODUCTION

There is currently considerable interest in the production of lenses with electronically controllable focal lengths which could be used in a variety of applications ranging from consumer electronics to specialist scientific applications. In this conference we present results of a novel type of switchable lens based on a fixed birefringence lens and a polarization switch (a ferroelectric liquid crystal lens). The first reference to this type of lens is in the patent literature[1] although, to the best of our knowledge, the concept has not been demonstrated in the open literature. Here we show results of birefringent lenses producing both variable focus and zoom

The lens design differs from other available technologies in that the basic focusing element is a fixed birefringent lens and that the variation in the focal power is effected by means of a secondary, polarization modulating, device. Using a fixed lens allows for very good optical quality, relatively high optical power, and for the possibility of more complex surface geometries. The performance of the lens is ultimately limited only by the polarization modulator used, and whilst there are a variety of methods available, we have chosen to use a ferroelectric liquid crystal (FLC), because of its simplicity, high speed, and ease of use.

FOCUS SWITCHING

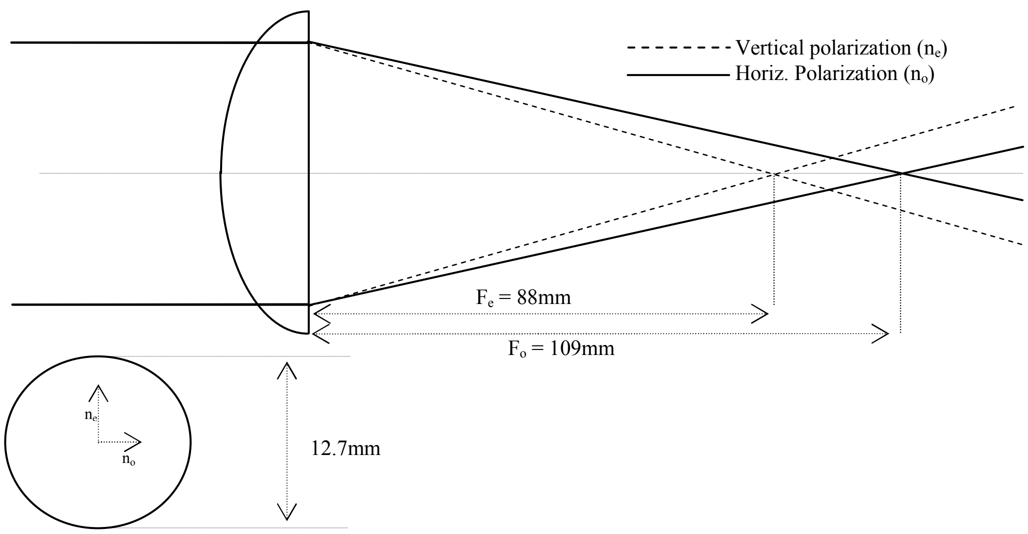

Fig. 1. Concept and specifications of the birefringent lens. The lens has two different focal lengths for light polarized along the extraordinary axis (blue lines) and the ordinary axis (red lines).

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The concept of a birefringent lens is illustrated in figure 1. The key property of the lens is that is has two focal lengths, corresponding to the ordinary and extraordinary refractive indices of the material. The material used was calcite, due to its high birefringence (0.172) in the visible, and the fact that it is readily machineable. The lens is plano-convex, with a diameter of 12.7mm and focal lengths of F_e=88mm and F_o=109mm (~f/7 and f/8.6 respectively) at a wavelength of 589nm, where F_e and F_o correspond to the extraordinary and ordinary focal lengths respectively. The lens was manufactured by Halbo Optics[2].

Figure 2 shows the basic focal-length switching system. The system comprises a birefringent lens, a linear polarizer and a switchable half-wave plate. The linear polarizer is aligned with either the ordinary or extra-ordinary axis of the lens, and the half-wave plate is aligned at 0^0 or 45^0 to the polarizer, depending on its switched state.

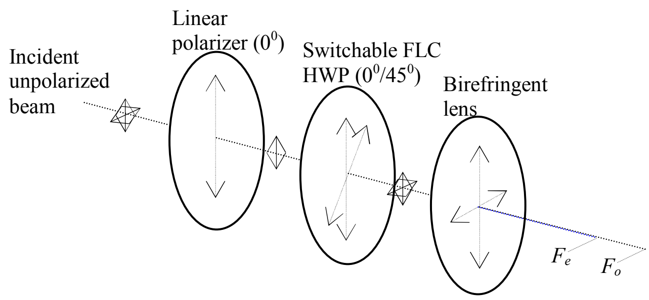

Fig. 2. Illustration of focus-switching setup. Light is first vertically linearly polarized and then selectively rotated by the FLC in order to select either the ordinary or extraordinary indices in the birefringent lens and hence either the extraordinary, F_e, or ordinary, F_o, focus.

The unpolarized incident light is linearly polarized at 0^0 by the polarizer. If the FLC is off, then the light remains polarized at 0^0 when it reaches the birefringent lens, and is thus aligned with the ordinary crystal axis and is focused at F_o. If the FLC is on, then the plane of polarization of its emergent light is rotated by 90^0, and is aligned with the extra-ordinary crystal axis, and is thus focused at F_e.

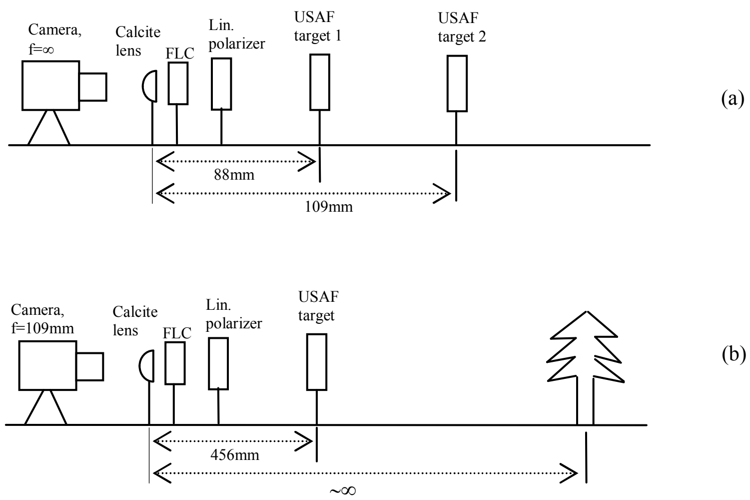

Figure 3. Optical arrangement of focus demonstrations

Figure 3 shows the optical configuration of the system used to obtain the results shown in figures 4 and 5. In figure 4 the targets are USAF test patterns, printed on two transparent sheets, conjugate with the focal planes for each of the lens focal lengths, as shown in figure 3(a). In figure 5 the lens and camera are arranged such that one focal length is conjugate on the edge of a ruler and the other focal length is conjugate on ~infinity(a tree some distance from the laboratory window).

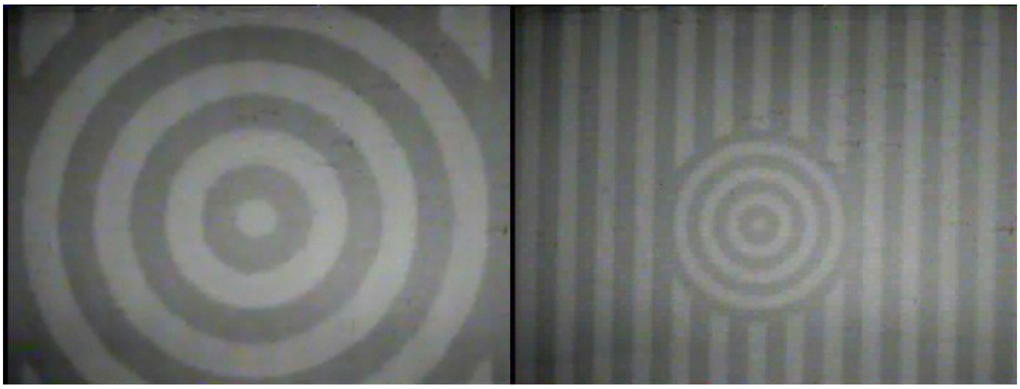

Fig. 4. Switching between image planes. The image on the left corresponds to a focal length of 88mm, the right to 109mm (1.1MB).

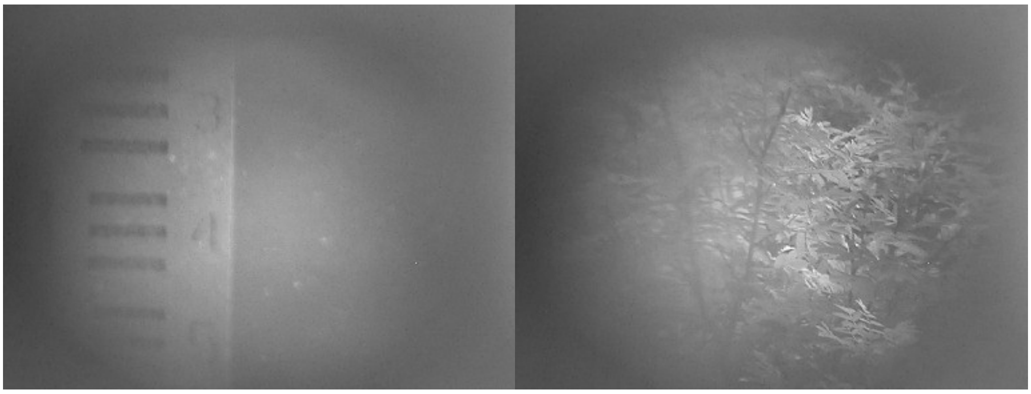

Fig. 5. Switching between image planes. The image on the left corresponds to a focal length of 88mm, the right to 109mm.

ZOOM LENS

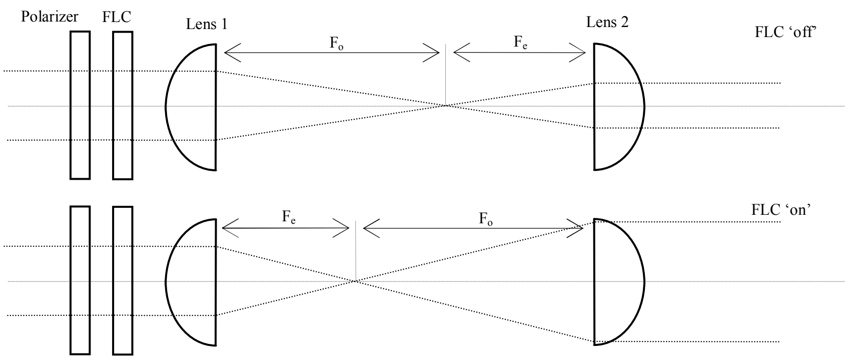

Fig. 6. Basic zoom lens design.

The lenses are set up with orthogonal optical axes so that they are confocal for either vertical or horizontal incident linear polarization.

The layout of a switchable zoom lens is illustrated in figure 6. The design is basic, and no attempt has been made to optimize the field of view or the chromatic performance of the device. Our aim here is to demonstrate the general utility of the technique.
Two identical birefringent lenses are used, arranged such that the ordinary crystal axis of the first lens is aligned with the extra-ordinary crystal axis of the second lens, and vice-versa. The lenses are separated by a distance (F_o+F_e), such that the lenses are confocal for both focal-length pairs. A polarizer and FLC are used, arranged as in the focus switching setup described in the previous section. The zoom factor is given by

$$Zoom = \left(\frac{F_o / F_e}{F_e / F_o} \right) = \left(\frac{F_o}{F_e} \right)^2 \approx \left(\frac{n_e}{n_o} \right)^2 . \qquad (1)$$

Thus the zoom factor is determined by the intrinsic birefringence of the material used, and not by the specific lens geometry. In the case of a calcite lens, this gives a zoom factor of ~0.649 (i.e. $\times 1.54$).

Figure 8 demonstrates zoom switching. The target is effectively at infinity (in practice at approx. 1km). The two calcite lenses are arranged as described above, at a separation of f_e+f_o, as illustrated in figure 7.

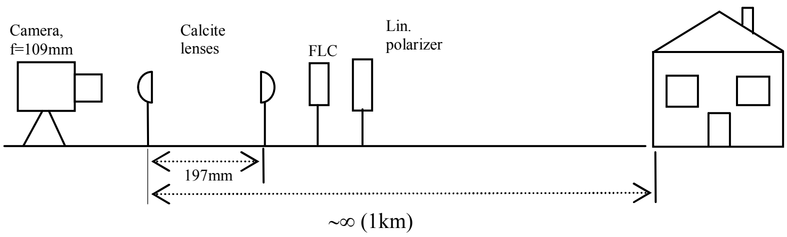

Figure 7. Optical arrangement of zoom demonstrations

Fig. 8. Zoom-switching. The image on the left corresponds to a magnification factor of x0.81, the right of x1.24

DISCUSSION.

We have demonstrated high speed focus and zoom switching with no moving parts and very low power consumption, using a fixed birefringent element and a single active polarization modulator.
It is obvious from figures 5-7 that the optical quality of the lens systems produced is less than ideal, with both chromatic aberration and vignetting apparent. It should however be noted that no attempt was made to optimize the optical designs, and that the intrinsic optical quality of the lenses appears to be good.
Focus and zoom switching were demonstrated at frequencies of up to 3KHz, which was the frequency limit of the FLC polarization flipper used. It should be noted that other types of polarization modulator are available, such as Kerr and Pockel cells, which can operate at much higher frequencies.
A potentially very interesting development of the lens system is the use of a stacked lens system, to overcome the limitation of a binary focal length

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2. Halbo Optics. www.halbo.com