Acousto-optic lens with very fast focus scanning

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We propose and experimentally demonstrate an acousto-optic cylindrical lens with a very fast (400-kHz) focal scanning. The lens is realized by use of two adjacent acousto-optic scanners with counterpropagating acoustic waves that have the same frequency modulation but a π phase difference. This scheme completely suppresses the lateral scan but adds the linear chirp of the two waves and thus functions as a fast focal-scan lens. We also demonstrate the use of this scanning lens in a very fast confocal profilometer. © 2001 Optical Society of America

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Lenses with a rapidly variable focal length have applications in many fields of optics such as imaging, microscopy, adaptive optics, material processing, optical data storage, and optical inspection. Several dynamic focusing methods have been realized by means of mechanically moving a focusing element, changing the curvature of a flexible mirror,[1] or changing the refraction index of a focusing device electronically by use of liquid crystals.[2,3] All these dynamic focusing methods are quite slow, and hence focal-scan rates are usually limited to far below 1 kHz. Faster focal scans have been demonstrated by use of electro-optic crystals,[4] which are limited to a specific light polarization, require high-frequency modulation of high voltages, and produce only modest scan spans (when measured in units of the focal depth).

In this Letter we propose, analyze, and experimentally demonstrate a new system that acts as an effective lens with rapidly variable focal length, using acousto-optic scanners (AOSs). It is well known that when the frequency of the acoustic wave in an AOS is chirped, it behaves like an effective cylindrical lens whose focal length is proportional to the chirp rate.[5] However, this well-known effect was not used to form a lens with rapidly variable focal length, since the focal variations are inherently accompanied by the normal transverse scan. Moreover, the focal variation was always regarded as an unwanted aberration that severely limits the resolution of very fast nonlinear or nonconstant scans.[5,6]

To eliminate the transverse scan and achieve a pure focal scan, we base our proposed system on two adjacent counterpropagating acoustic waves with a synchronized frequency chirp, whose transverse scans subtract to cancel each other, whereas their focal scans add. We demonstrate such a scan of the focal distance at a rate of 400 kHz and use this lens to construct a rapid confocal profilometer. Our discussion is applied to one-dimensional (cylindrical) focal scans, but we can readily generalize it to two-dimensional (spherical) focal scans by cascading two orthogonal one-dimensional scanners.[7]

The optical setup for our configuration is illustrated in Fig. 1. The setup is based on two adjacent and counterpropagating acoustic waves with velocity v in the acousto-optic crystal, which have nonconstant acoustic frequencies $f_1(t)$ and $f_2(t)$. The Bragg angles of the two acoustic waves are adjusted for maximum efficiency of the $+1$ and -1 diffraction orders of the first and second acoustic waves, respectively. Neglecting the distance between the acoustic waves, the total diffraction angle across the beam in the $(+1, -1)$ order is

$$\alpha(x,t) = \frac{\lambda}{v}\left[f_1(t + x/v) + f_2(t - x/v)\right], \tag{1}$$

where $x = 0$ is chosen at the center of the laser beam, which is at equal distance from the two opposite transducers, and λ is the wavelength of the light. By choosing $f_1(t) = f_2(t)$, we recently demonstrated how a pure transverse scan can be obtained even for nonlinear or nonconstant scans.[8] There, the unwanted focal shifts were viewed as aberrations, and their suppression resulted in a large improvement in the resolution of very fast nonlinear scans. Here, we demonstrate the exact opposite, namely, a pure focal scan that results from the complete suppression of the lateral scan. In the analysis we consider two simple examples of a linear chirp and a sinusoidal chirp of the acoustic frequencies.

Consider first a linearly chirped acoustic frequency $f_1(t) = f_{\min} + at$, with a chirp rate

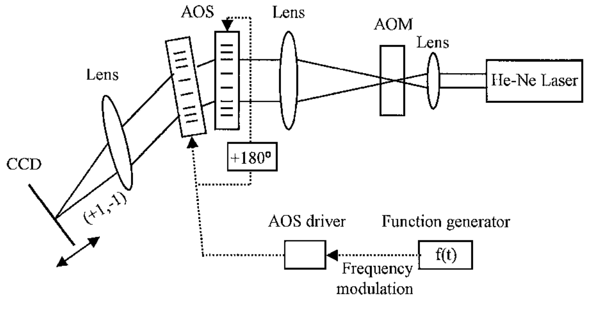

Fig. 1. Schematic experimental setup. A laser beam passes two AOSs with counterpropagating sound waves, with a 180° phase shift between their frequency-modulating signals. The light is focused on a CCD camera that is mounted on a translation stage and used to measure the focal distance. For this measurement, an acousto-optic modulator (AOM) is used to pulse the beam synchronously with the scan, and the focus position changes with the pulse delay time.

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$a = (f_{\max} - f_{\min})/T_{\text{scan}} = \Delta f/T_{\text{scan}}$, where $f_{\min}$ and $f_{\max}$ are the minimal and maximal acoustic frequencies, and T_{scan} is the scan period. If we choose $f_2(t) = f_{\max} - at$, Eq. (1) yields

$$\alpha_{\text{linear}}(x,t) = \frac{\lambda}{v}\,(2f_{\text{center}} + 2ax/v) = \alpha_{\text{off-axis}} + x/F\,, \tag{2}$$

with $f_{\text{center}} = (f_{\max} + f_{\min})/2$. Equation (2) represents a time-constant (no time dependence) one-dimensional (cylindrical) off-axis lens with an off-axis angle of $\alpha_{\text{off-axis}} = 2\lambda f_{\text{center}}/v$, and a focal length of

$$F = \frac{v^2}{2a\lambda} = \frac{v^2 T_{\text{scan}}}{2\lambda\Delta f}\,. \tag{3}$$

By changing the chirp rate a electronically, F is changed, whereas $\alpha_{\text{off-axis}}$ remains unchanged. Hence a pure focal scan (without any transverse scan) is indeed obtained. To maintain the lens over times longer than T_{scan}, one must realize a periodic scan in the form of a sawtooth.[9]

Fast periodic focal scans can be obtained by use of two cosine-modulated acoustic frequencies with a π phase shift between them: $f_1(t) = f_{\text{center}} + {}^1\!/_2\,\Delta f\,\cos(2\pi t/T_{\text{scan}})$, and $f_2(t) = f_{\text{center}} - {}^1\!/_2\,\Delta f\,\cos(2\pi t/T_{\text{scan}})$. Using these frequencies in Eq. (1) yields

$$\alpha_{\text{cosine}}(x,t) = \frac{\lambda}{v}\,[2f_{\text{center}} - \Delta f\,\sin(2\pi t/T_{\text{scan}}) \times \sin(2\pi x/vT_{\text{scan}})]\,. \tag{4}$$

For $|x| \ll vT_{\text{scan}}$ the second sine function is well approximated by a linear function and hence here, as well, $\alpha(x,\,t)$ approximates a cylindrical lens, but now with a focal length that varies in time according to

$$F(t) = \frac{F_{\text{AOS}}}{\sin(2\pi t/T_{\text{scan}})} = \frac{v^2 T_{\text{scan}}}{2\pi\lambda\Delta f\,\sin(2\pi t/T_{\text{scan}})}\,. \tag{5}$$

For a practical focal-scan system we consider the modulated lens adjacent to a fixed lens with focal length $F_0 \ll F_{\text{AOS}}$. With the thin-lens approximation, the focal scan of the combined lens is found to be $\Delta F_{\text{combined}} \simeq 2(F_0)^2/F_{\text{AOS}}$. The number of resolvable points (NRP) that are accessible for our focal scan is defined as the ratio between $\Delta F_{\text{combined}}$ and the focal depth of the combined lens. This (FWHM) focal depth is given by $\eta\lambda(F_{\text{combined}}/D)^2 \simeq \eta\lambda(F_0/D)^2$, where D is the aperture of the AOS, and η is a constant that depends on the beam shape (i.e., for a laser beam with a constant intensity over the size D, $\eta \simeq 7$).[10] We get

$$\text{NRP} = \left(\frac{4\pi}{\eta}\right)\frac{(T_{\text{access}})^2\Delta f}{T_{\text{scan}}}\,, \tag{6}$$

where $T_{\text{access}} = D/v$ is the access time, i.e., the time that it takes for the acoustic wave to cross the aperture of the AOS. One can obtain a large NRP by use of a large T_{access} (i.e., a large beam diameter and slow acoustic velocity) as long as condition $T_{\text{scan}} \gg T_{\text{access}}$ is met, to ensure good linearity of the chirp and hence low aberrations. For example, using readily available parameters of $\Delta f = 50$ MHz, $T_{\text{access}} = 10\ \mu$s, and $T_{\text{scan}} = 50\ \mu$s, and with $\eta = 7$, we get a NRP of 180. Moreover, this scheme also permits much faster scans with a NRP of ~10, as is demonstrated below by our experiment. Note that with a high signal-to-noise ratio the actual focal resolution of the system can be much smaller than the focal depth.

We performed an experiment to test the validity of the AOS effective lens with a cosine modulation of the focal length. For the experiment, we used the configuration of Fig. 1. A He–Ne laser beam with $\lambda = 633$ nm and $D = 2.6$ mm was passed through two adjacent AOSs[11] with $f_{\text{center}} = 110$ MHz, $\Delta f = 18$ MHz, $T_{\text{scan}} = 2.5\ \mu$s, and $v = 4200$ m/s, and hence $T_{\text{access}} = 0.62\ \mu$s. The (+1, −1) diffraction order was focused by a lens with $F_0 = 150$ mm focal length onto a CCD camera. To measure the spot size during the scan, we synchronously pulsed the laser beam, using a third (fixed frequency) acousto-optic modulator. By tightly focusing the beam on this modulator and reducing the pulse length to <100 ns, we ensured a negligible contribution of the finite pulse time to the resolution. The acoustic frequencies $f_1(t)$ and $f_2(t)$ were scanned sinusoidally with a π-rad phase shift between them, and the focal distance was measured as a function of the pulse delay time. The results are shown in Fig. 2, together with a sinusoidal fit. As can be seen from the figure, a sinusoidal scan of the lens focal length from 120 to 180 mm was obtained ($\Delta F = 60$ mm), in good agreement with a calculation based on Eq. (5), modified to include the actual distance between the AOSs and the fixed lens, which was 150 mm in the experiment. With a larger frequency span ($\Delta f = 33$ MHz), we measured $\Delta F = 90$ mm, as expected. We also confirmed that no lateral shift of the spot (x scan) exists and that the spot size in focus (~44 μm, in agreement with a diffraction-limited spot for $D = 2.6$ mm) is not increased compared with the static one. Finally, we

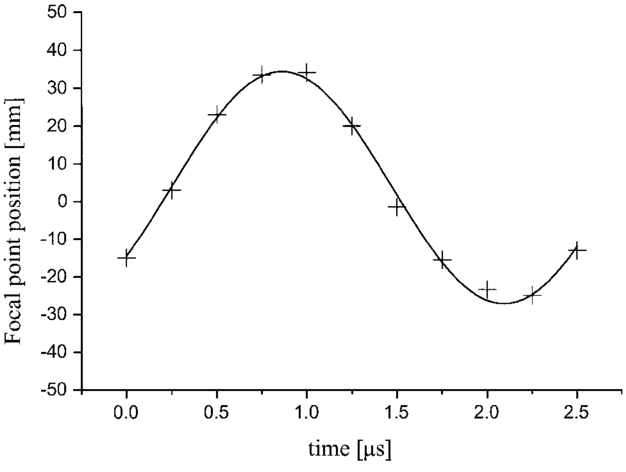

Fig. 2. Measured position of the focal plane as a function of the pulse delay (+), around the focus of the AOS lens combined with a 150-mm lens. The solid curve is a sinusoidal fit with a frequency of 400 kHz and a span of 60 mm.

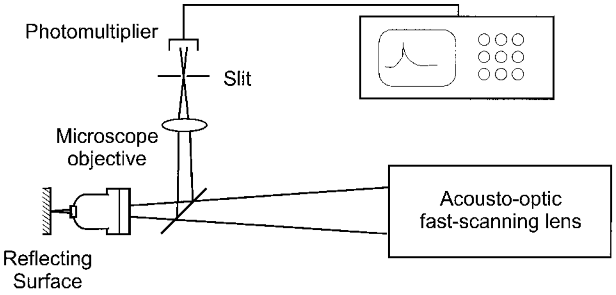

Fig. 3. Setup for ultrafast confocal profilometer. The AOS fast focal-scan lens is used to scan the focus of the combined lens. A photomultiplier tube is used to measure the intensity of the light that passes the slit in the conjugate focal plane.

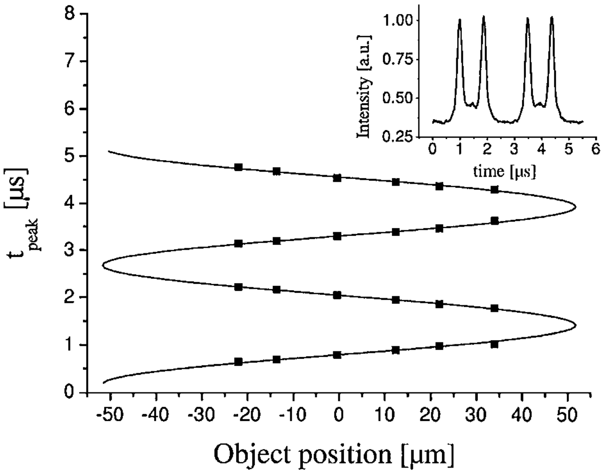

Fig. 4. Calibration of the profilometer: measured times of the peaks in the PMT signal as a function of the position of the mirror (■). The data are fitted with a sinusoidal scan at a rate of 400 kHz and a span of 100 μm. The inset shows a typical scan of the PMT signal over two scan periods. The time of the peaks is a measure of the position of the reflecting object along the z direction.

measured the focal depth of the combined lens to be 12 mm, yielding an experimental NRP of 5.

We also demonstrated an application of our variable-focus lens for a confocal profilometer, using the configuration shown in Fig. 3. All the parameters of the AOS lens were the same as above, but here it was combined with a 10× microscope objective for improved depth resolution. Here the laser was not pulsed with the third AOS but was continuously on. A flat object was placed at the vicinity of the focal plane of the combined lens, and the on-axis reflected light was reflected with a beam splitter, focused on a slit, and collected by a fast photomultiplier. The width of the slit was adjusted to be equal to the spot size, which gives the best NRP. The light intensity that passed through the slit as a function of time during two focal scans of period 2.5 μs each is shown in the inset of Fig. 4. As can be seen, only two times during a focal-scan period does the focus coincide with the surface of the flat object, and hence the confocal condition is fulfilled and a large light intensity passes through the slit. Therefore, the relative delay times of these maxima are a measure of the object's z position, once the focal-scan parameters are calibrated. We performed such a calibration by moving the object along the z axis, using a calibrated piezoelectric transducer (PZT) and repeating the measurement for each PZT voltage. The resulting peak positions as a function of the PZT displacement are presented in Fig. 4, in which four peak positions are shown for each PZT position. The peak positions are extremely well fitted by a sinusoidal scan at a 400-kHz rate and an amplitude of 100 μm, which is the focal-scan range in this case. The FWHM of the peaks is 200 ns, which corresponds to 24 μm, resulting in a NRP of 4.3. From the signal-to-noise ratio of our measurement, which is >300, the depth resolution of the profilometer is estimated as $\sigma_z < 1\ \mu$m.

To conclude, we have proposed a new scheme for a very fast variable-focus lens based on two AOSs with counterpropagating sound waves. We experimentally demonstrate a 400-kHz scan of the focus and use the scanning lens in a simple ultrafast confocal profilometer. By addition of two additional AOSs, perpendicular to the first two, it is possible to construct a two-dimensional (spherical) lens with comparable scan rates, at the expense of lower power efficiency.[12] It is also possible to realize a general three-dimensional beam scan by scanning of the off-axis angle of the lens (which is controlled by f_{center}), at the expense of a reduced Δf (and hence a reduced longitudinal scan range).

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9. Such a realization causes difficulties, first, because of the jumps in the chirp at the end of every cycle and, second, because of the higher harmonics that are needed, which limit the available scan speed.
10. Our analysis is readily adapted for other laser beam shapes, such as a Gaussian beam, with small changes of numerical constants.
11. Brimrose Model TEF-110-60.
12. A diffraction efficiency >70% for the entire Δf is achievable in commercial AOSs, resulting in >25% power efficiency for the spherical lens configuration.