Acousto-optic scanning system with very fast nonlinear scans

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A very fast (>100 kHz) acousto-optic scanning system, which relies on two counterpropagating acoustic waves with the same frequency modulation, is proposed and experimentally demonstrated. This scheme completely suppresses linear frequency chirp and thus permits very fast nonlinear scans and nonconstant linear scans. By changing the phase between the modulating signals, this scheme also provides very fast longitudinal scans of the focal point. © 2000 Optical Society of America

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Acoustic-optic scanners (AOS's) have no moving parts and are thus capable of scanning laser beams much faster than any mechanical scanner.[1] The limitation on their scanning speed arises from the transition (or access) time, T_{access}, of the acoustic wave across the width of the laser beam. In most present applications a scan angle that is linear with time is desired $[\alpha(t) = at]$ and is achieved with linear chirping of the acoustic-wave frequency, $f(t)$. For such linear scans the scan rate can approach T_{access}^{-1}, since the linear chirp acts as an effective constant (time-independent) cylindrical lens, which can be readily compensated without any reduction in the number of resolvable points (NRP).[2] However, nonlinear scans (or scans with a nonconstant rate or span) must inherently have a nonconstant frequency chirp, which results in large aberrations and dramatically reduces the NRP for fast scans.

Nonlinear (or nonconstant) acousto-optic scanners recently attracted much attention for a variety of applications. These scanners were used for generating two-dimensional circular scans to form dark optical dipole traps for ultracold atoms[3] and for stirring[4] and rotating[5] Bose–Einstein condensates. In addition, these scanners are essential for ultrafast laser vector plotters in which arbitrary (and hence nonlinear) scans are required for efficient plotting of sparse information over a large area.

In this Letter we first analyze the combined limitations on speed and resolution for nonlinear AOS's and show that they are much worse than for linear scanners. Next we propose, analyze, and experimentally demonstrate an improved scanning system, based on two adjacent counterpropagating acoustic waves, which largely improves the performance of nonlinear (or nonconstant) scans. Finally, we show that the new system can also be applied to ultrafast scans of the laser beam focus along the optical axis. Our discussion is applied to one-dimensional scans, but one can readily generalize it to two-dimensional scans by cascading two orthogonal one-dimensional scanners.[6]

Consider a uniform laser beam with diameter D and wavelength λ that is Bragg deflected by a perpendicular acoustic wave with frequency $f(t)$ and velocity v in an acousto-optic crystal.[7] The angular scan span in the first diffraction order is $\Delta\alpha = \Delta f \lambda / v$, where Δf is the acoustic frequency span. Dividing $\Delta\alpha$ by the diffraction-limited angular spread, λ/D, yields the so-called static (low scan rate) NRP as

$$\text{NRP}_{\text{static}} = \Delta f D / v = \Delta f T_{\text{access}} . \quad (1)$$

Equation (1) indicates that for a large value of $\text{NRP}_{\text{static}}$, large Δf and T_{access} are required. Scanners with Δf above 100 MHz are typically very expensive and suffer from reduced diffraction efficiencies, increased acoustic-wave absorption, and heating. Hence, scanners with large $\text{NRP}_{\text{static}}$ mostly rely on large T_{access}, which is achieved by a combination of a slow acoustic velocity (using shear-mode acoustic waves) and a large laser beam diameter.

Next we include the effects of the scan time, T_{scan}, on the resolution. For a linear frequency chirp, which acts as a constant effective cylindrical lens,[2] T_{scan} can approach T_{access}, and hence the dynamic (or fast-scan) resolution limit is simply

$$\text{NRP}_{\text{dynamic, linear}} \lesssim \Delta f T_{\text{scan}} . \quad (2)$$

However, for arbitrary (or totally random) scans, which include $\text{NRP}_{\text{dynamic}}$ resolution points in a random order, T_{scan} must be $\text{NRP}_{\text{dynamic}} \times T_{\text{access}}$. For a given scan time there is an optimal value for the access time, $T_{\text{access}}^{\text{opt}} = (T_{\text{scan}}/\Delta f)^{1/2}$, which yields a dramatically worse limitation on the optimal resolution:

$$\text{NRP}_{\text{dynamic, random}} \lesssim (\Delta f T_{\text{scan}})^{1/2}. \quad (3)$$

For common parameters of $\Delta f = 100$ MHz and $T_{\text{scan}} = 10\ \mu$s, the linear scan has NRP ~ 1000 as compared with ~ 30 for the random scan. This trend is in exact analogy to the NRP of space-invariant optical transformation (e.g., imaging) and space-variant ones, which scale as (D/λ) and $(D/\lambda)^{1/2}$, respectively, according to Gabor's information theory.[8] For the intermediate case, in which the desired scan is neither exactly linear nor totally random, information theory suggests that it may be possible to improve expression (3) by exploiting information reduction (or symmetry) of $\alpha(t)$.[8,9]

Figure 1 shows our configuration for a fast nonlinear AOS with improved resolution. It is based on two adjacent and couterpropagating acoustic waves with the same acoustic frequency, $f(t)$. The Bragg angles of the two acoustic waves are adjusted to

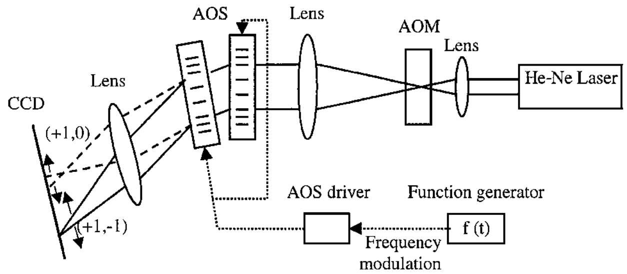

Fig. 1. Experimental setup: A laser beam is modulated by a fast acousto-optic modulator (AOM) and collimated. The beam then passes through two AOS's with opposite acoustic waves carrying the same (nonlinear) frequency chirp. The $(+1,0)$ order, which is modulated by only one AOS, has a reduced NRP, owing to the varying chirp. However, the $(+1,-1)$ order, which is modulated by both AOS, has larger NRP, owing to suppression of the first-order chirp.

maximize the 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 (see Fig. 1)

$$\alpha(x,t) = \frac{\lambda}{v}[f(t+x/v) + f(t-x/v)], \quad (4)$$

where $x = 0$ is chosen at the center of the laser beam, which is at equal distance from the two opposite transducers.

For a linear frequency chirp, Eq. (4) yields $\alpha(x,t) = 2\alpha_{\text{single}}(x=0,t)$; i.e., the scanning angle is twice that of a single scanner, and the chirp is completely eliminated (no x dependence), and hence no compensating cylindrical lens is needed. Since the chirp is completely eliminated regardless of T_{scan} and Δf, they can both be changed extremely fast without having to replace (or mechanically move) a compensating lens, as is the case with conventional scanners.[1]

For nonlinear scans, Eq. (4) indicates that our new configuration suppresses the linear chirp term, which is proportional to the first derivative of $f(t)$, leaving only the higher-order derivatives and thus reducing aberrations and improving the resolution of the fast scans. As an example, we analyze a cosine scan

$$f(t) = f_0 + \frac{1}{2}\Delta f \cos(2\pi t/T_{\text{scan}}), \quad (5)$$

which is useful for two-dimensional circular or elliptical scans.[3] Here the linear chirp [the first derivative of $f(t)$] is in the range $\pm\pi\Delta f/T_{\text{scan}}$, yielding for the single acoustic wave the limitation $\text{NRP}_{\text{dynamic, cos}} \lesssim (1/\pi\, \Delta f T_{\text{scan}})^{1/2}$. For our configuration, Eq. (4) yields

$$\alpha(x,t) = \frac{\lambda}{v}[2f_0 + \Delta f \cos(k_{\text{scan}}x)\cos(2\pi t/T_{\text{scan}})], \quad (6)$$

where $k_{\text{scan}} = 2\pi/vT_{\text{scan}}$ is the modulation wave number. Near $x = 0$, $\alpha(x,t)$ has no linear gradient at any time t. To calculate the NRP for our configuration we require that the variations of $\alpha(x,t)$ across the laser beam diameter $(-D/2 < x < D/2)$ are smaller than the static resolution limit of $\lambda\Delta f/v\text{NRP}^{\text{new}}$. Using a quadratic approximation for the cosine function and optimal T_{access} finally yields the dynamic optimal NRP to be

$$\text{NRP}^{\text{new}}_{\text{dynamic}} \lesssim (\Delta f T_{\text{scan}})^{2/3} \quad (7)$$

$$\lesssim 4^{1/3}\left(\frac{f''_{\max}}{\Delta f}\right)^{-1/3}(\Delta f T_{\text{scan}})^{2/3}. \quad (8)$$

Expression (7) describes the cosine scan, and expression (8) is an extension to the general nonlinear scan. Here $f'' = \partial^2 f/\partial\tau^2$ (with $\tau = t/T_{\text{scan}}$) is the normalized second derivative of the desired scan function, $f(t)$, and the contribution of higher derivatives was neglected. Expression (8) indicates that our configuration, which completely corrects the variable linear chirp term in nonlinear scans, is next limited by the second-order derivative. Hence the dependence of the NRP on $\Delta f T_{\text{scan}}$ (power of 2/3) is indeed intermediate between the linear (power of 1) and the random (power of 1/2) scans. Note that when f'' approaches zero, expression (8), which predicts an infinite NRP, should not be used, since the NRP cannot exceed the limit of Eq. (1).

For the experiment we used the configuration in Fig. 1. A He–Ne laser beam with $\lambda = 633$ nm and $D = 2.6$ mm passed through two adjacent AOS's[10] with $f_0 = 110$ MHz, $\Delta f = 60$ MHz, 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 a 150-mm focal distance onto a CCD camera together with the $(+1,0)$ order that was used for comparison.[11] 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 frequency, $f(t)$, was scanned according to Eq. (5) with the parameters given above.

Figure 2 shows the measured intensity cross sections for the $(+1,0)$ order (single acoustic wave) with a very slow ($f_{\text{scan}} = T^{-1}_{\text{scan}} = 1$ kHz; Fig. 2A) and a very fast ($f_{\text{scan}} = 140$ kHz; Fig. 2B) scan rate, with

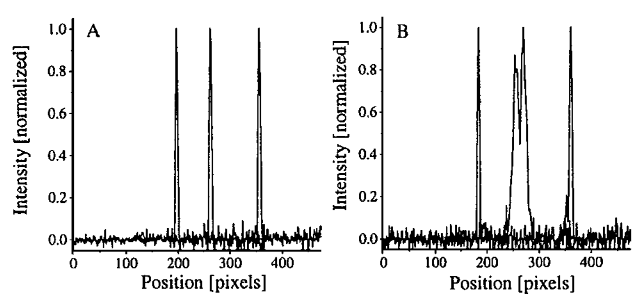

Fig. 2. Measured intensity cross sections at the focal plane, for a cosine scan with one acoustic wave at a scan frequency of A, 1 kHz and B, 140 kHz. At each frequency, three spots are shown: at the extreme right (pulse at $t \approx 0$), center ($t \approx T_{\text{scan}}/4$), and extreme left ($t \approx T_{\text{scan}}/2$) of the scanning range.

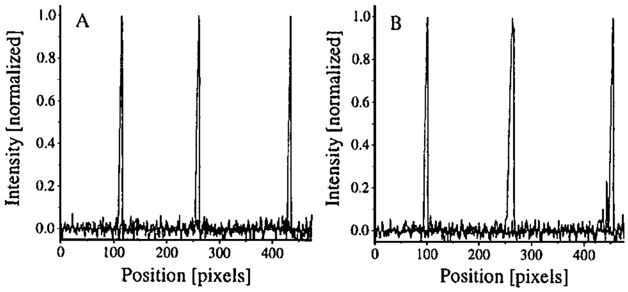

Fig. 3. Same as Fig. 2 but for a cosine scan with two opposite acoustic waves.

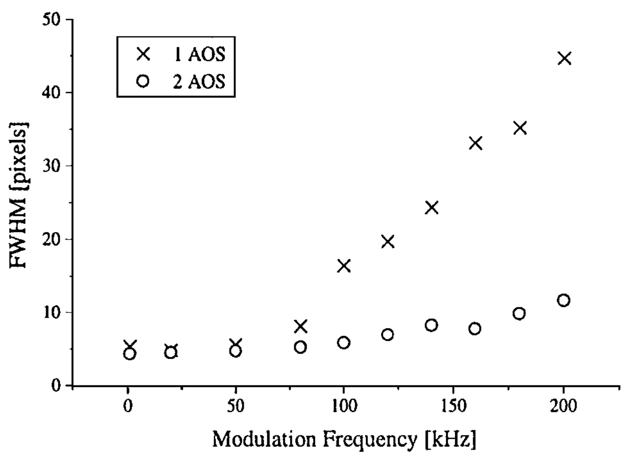

Fig. 4. Measured maximal spot size (FWHM) at the center of the scanning range ($t \approx T_{\mathrm{scan}}/4$) for a cosine scan with ($\times$) one and ($\bigcirc$) two opposite acoustic waves as a function of the modulation frequency.

the pulse in the extreme left, the middle, and the extreme right of the scan line. The static NRP (the scan span over the maximal FWHM spot size in Fig. 2A) was $\mathrm{NRP}_{\mathrm{static}} = 42$, in good agreement with the calculated value of 37. For the fast scan (Fig.2B), the spot size at the center ($t = T_{\mathrm{scan}}/4$), where a large linear chirp exists [see Eq. (5)], is much larger than in the two sides ($t = 0$ and $t = T_{\mathrm{scan}}/2$), where the linear chirp is zero. The NRP in this case is reduced to 8.

Figure 3 shows the same measurements for the $(+1, -1)$ order of our two-acoustic-wave configuration, again for $f_{\mathrm{scan}} = 1$ kHz (Fig. 3A) and $f_{\mathrm{scan}} = 140$ kHz (Fig. 3B). The static NRP (Fig. 3A) is now 78, approximately twice the $\mathrm{NRP}_{\mathrm{static}}$ of the single acoustic wave of Fig. 2, since the spot size is unchanged and the scan span is doubled. However, a dramatic effect occurs for the very fast scan (Fig. 3B): All three spots, including the one at the scan center, remain nearly unchanged and $\mathrm{NRP}_{\mathrm{dynamic}} = 46$, which is close to the optimal value of $\lesssim 57$ calculated from expression (7) (and approximately six times larger than for Fig. 2B).

Figure 4 shows the spot size of the central spot ($t = T_{\mathrm{scan}}/4$) as a function of the scan frequency for the $(+1, -1)$ and $(+1, 0)$ orders for a cosine scan with the same parameters as Figs. 2 and 3. As can be seen from the figures, our configuration suppresses the spot-size increase that is due to the dynamic (chirping) effects for much faster scans than the conventional scanner, permitting a combination of both high resolution and ultrafast scans.

Finally, Eq. (6) predicts that near $x = \pi/k_{\mathrm{scan}}$ (or, alternatively, by introduction of a phase shift of π rad between the cosine modulations of the counterpropagating acoustic waves) the lateral scan (x scan) of the $(+1, -1)$ order vanishes, and a pure longitudinal scan of the focal point is obtained (i.e., a linear chirp that changes in time between $\mathrm{d}f/\mathrm{d}x = \pm \Delta f k_{\mathrm{scan}}$). We saw this effect in our experiments for the phase-shifted case, in which the focal point was longitudinally scanned at a rate of 140 kHz.

To conclude, we proposed an improved configuration for fast nonlinear and linear nonconstant acousto-optic scans by use of the same frequency-modulated signal for two opposite acoustic waves. We demonstrated the new scheme with a cosine scan, where an improvement in resolution of approximately six times over the single-acoustic-wave case was achieved. Even larger improvement is expected for AOS's with larger D and slower v. This concept of counter-propagating gratings can also be directly applied to nonlinear and nonconstant holographic scanners.[12]

A combination of ultrafast laser beam scan over large spans combined with high spatial resolution can find applications for optical information processing, laser vector plotters, laser material processing, laser inspection of microelectronic chips and boards, and laser manipulation of atoms, ions, and microscopic particles.

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