Since the introduction of the Z scan,\textsuperscript{1} a sensitive single-beam technique for measuring nonlinear refraction (NLR), several variations have been introduced to enhance the technique. These include measurements in the presence of nonlinear absorption\textsuperscript{2} (NLA), the two-color Z scan for the study of nondegenerate nonlinearities,\textsuperscript{3,4} the time-resolved Z scan,\textsuperscript{4,5} and measurements of the anisotropy of NLR.\textsuperscript{6} Most of these experiments have been performed with low-repetition-rate (=10-Hz) picosecond or nanosecond laser systems. Even with these low data-acquisition rates, the technique has demonstrated a sensitivity to wave-front distortion of $\lambda/300$ for a signal-to-noise ratio (S/N) of unity. It has been shown theoretically that a threefold enhancement of the Z scan’s sensitivity to NLR can be achieved by the use of a lens between the sample and the aperture,\textsuperscript{7} but this has yet to be realized experimentally. Recently it was demonstrated that the use of a top-hat beam profile in the Z scan results in an increase in sensitivity to NLR of $\approx 2.5$.\textsuperscript{8} Here we introduce a simple modification of the Z-scan technique that provides greater than an order-of-magnitude enhancement of the S/N. This modification involves replacing the far-field aperture used in the standard Z scan with an obscuration disk that blocks most of the beam. The resulting pattern of light that passes around the edge of the disk, shown in the inset of Fig. 1, appears as a thin halo of light, reminiscent of a solar eclipse; hence this technique is named the eclipsing Z scan (EZ scan). This modification of the Z scan, accompanied by methods to compensate for fluctuations of the beam spatial profile, results in a sensitivity to induced wave-front distortion of $\approx \lambda/10^4$ with a S/N of unity from a 10-Hz repetition-rate pulsed laser. Significantly higher sensitivities should be possible for more stable or higher-repetition-rate laser systems.

The EZ-scan experimental setup is shown in Fig. 1, where the aperture of the Z scan has been replaced by an opaque disk in the far field. As with the Z scan, a thin nonlinear sample is scanned along the $Z$ axis of a focused Gaussian beam. In the case of a self-focusing nonlinearity ($n_2 > 0$, where $n = n_0 + n_2 I$), the sample will behave as a positive lens near the focus. Thus, for the sample positioned prior to focus, the far-field beam divergence is increased, and more light will pass by the disk in the far field. Note that this is exactly opposite the decreased transmittance of the aperture for a Z scan. With the sample positioned after the focal plane, the effect of the sample is to collimate the beam, and the disk blocks more of the light. Consequently, in the EZ scan a self-focusing medium results in an increase in transmittance (peak), followed by a decrease (valley) as the sample is scanned from in front of to behind the focus. For self-defocusing media, the positions of the valley and peak are reversed.

For a thin sample\textsuperscript{9} this behavior can be modeled by the separated equations for irradiance, $I$, and induced phase shift, $\Delta \phi$: $\frac{dI}{dz} = -\alpha I$ and $\frac{d\Delta \phi}{dz} = k n_2 I(z')$, where $\alpha$ is the linear absorption coefficient, $k = 2\pi / \lambda$, and $\lambda$ is the wavelength in vacuum. $z'$ is the depth within the sample, as distinct from $Z$, the sample position with respect to the beam waist. In our modeling we assume the incident beam to be Gaussian. The integrated phase shift for a sample of length $L$ follows the radial variation of the beam to be Gaussian.
that the sensitivity is limited to $A/700$. The increase in the reference arm, but performing a Z scan, we find that the rms noise can be reduced to $0.1\%$ with this $100$-shot average per data point shown in Fig. 2, the S/N by a factor of $3-5$. In our system, with the ratio of energies $D_3$ and $D_2$, we can increase the $S/N$ by a factor of $3$. For $S < 1$, the aperture transmittance in a Z scan, which is $S = 1 - \exp(-2\alpha L)^2$, where $w_0$ is the beam radius at the disk plane in the linear regime. We see from Fig. 3 that for large enhancement to be obtained, $S$ must be within a few percent of unity. In practice this limits the maximum sensitivity enhancement as the energy reaching the detector becomes too small to detect. For our system $S = 0.99$, as used in the inset in Fig. 1, gave good enhancement while still giving sufficient energy for easy detection. Note that for $S = 0.5$, corresponding to $\alpha = w_0/2.35$, the sensitivities of the $Z$ scan and $EZ$ scan are identical, as expected.

For a large disk, $0.995 > S > 0.98$ (the useful range for this technique), and a small nonlinear phase shift $\Delta \Phi_0 < 0.2$, we find a similar empirical linear relationship between $\Delta T_{pv}$ and $\Delta \Phi_0$ for the $EZ$ scan:

$$\Delta T_{pv} = 0.68(1-S)^{-0.44}|\Delta \Phi_0|,$$

which is accurate to within $\pm 3\%$. For the above range of $S$ the spacing between the peak and valley,
The presence of a far-field obscuration disk also results in an increase in sensitivity to NLA. For example, in the case of reverse saturable absorption or two-photon absorption the center portion of the beam is more strongly absorbed than the wings, thereby spatially broadening the beam as it leaves the sample. Propagation transforms this near-field broadening into far-field narrowing, causing more of the beam to be blocked by the disk and enhancing the fractional change in transmittance seen by the detector. For similar reasons, an obscuration disk also enhances the effect of saturable absorption.

In summary, we have demonstrated that the EZ scan, in combination with beam fluctuation compensation, provides a highly sensitive method for measuring small nonlinearly induced phase shifts, while retaining the ability to discriminate between NLR and NLA, and for determining the sign of each of these effects. The method is particularly relevant to the current problem of determining nonresonant nonlinearities in thin films without the need for waveguide coupling. For films of thickness \( d = \lambda \), a sensitivity to wave-front distortion of \( \lambda/10^4 \) corresponds to a sensitivity to index changes of \( \Delta n = 10^{-4} \).

As we observed from Fig. 4, the enhancement in sensitivity comes at the expense of a reduction in accuracy caused, we believe, by deviations from a Gaussian irradiance distribution. We therefore recommend use of this technique with a known reference to calibrate the system (for our system, without such calibration, the absolute accuracy was within 18%). The Z scan is still the method of choice unless the S/N is a problem.

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