Acousto-optic modulation of GW-scale beams in ambient air

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ABSTRACT

Control over the parameters of a laser beam such as intensity and phase provides an important basis of modern photonics. Established control schemes, however, cover only a limited parameter range. We employ intense ultrasound fields in ambient air, enabling control of laser light in extreme parameter regimes. We acousto-optically modulate ultrashort pulses at 1030 nm with a peak power of 20 GW efficiently ($> 50\%$) in ambient air. Further, we show excellent beam profile conservation and separability of diffracted and transmitted beams. Finally, our approaches show that light control can prospectively be translated from solid-state media to the gas phase by means of intense ultrasound, considerably widening the scope of established light control methods.

Keywords: Photonics, acousto-optics, gigawatt, ultrafast

1. INTRODUCTION

The control of light is the key to modern photonics. It enables a wide range of applications, such as laser material processing, optical metrology, and laser spectroscopy. Control over the different properties of light is typically achieved by means of optical elements, such as lenses, mirrors, and diffractive elements. These elements are limited in their application by the properties of the employed optical media. These media are typically solid-state dielectric materials, such as glasses or crystals. Their performance is typically limited by the optical damage threshold, the optical peak power, and the wavelength-dependent linear absorption. For example, transmissive solid-state acousto-optic modulators (AOMs) are limited to optical peak powers in the megawatt-range[1] and to wavelengths of above about 300 nm.[2] The main advantage of solid-state media is their high refractive index, which allows for a large change in the refractive index Δn.

In order to venture into the extreme parameter regimes of light, including high peak powers, short wavelengths, and high intensities, new approaches are required. One approach is to use gases as an optical medium. Unlike solids, gases are resistant to damage and can handle peak powers that are about three orders of magnitude higher with minimal dispersion across broad spectral areas. However, their refractive index is nearly 1, which

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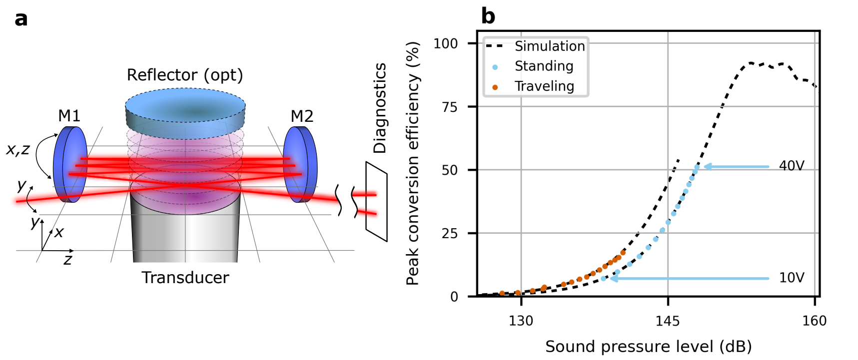

Figure 1. **a**, Schematic of the experimental setup. A multi-pass scheme is enabled by mirrors M1 and M2, guiding the beam seven times through the acoustic field above the ultrasound transducer. An optional reflector can be mounted to create a resonant standing acoustic wave. **b**, Measured diffraction efficiency as a function of the sound pressure level (SPL) for two configurations, with acoustic reflector (Standing) and without (Traveling). The dashed lines are the corresponding numerical simulations (3+1d split-step Fourier method). Adapted from ref. [8] under a Creative Commons licence CC BY 4.0.

restricts Δn for gas-based photonic systems. Moreover, establishing a static refractive index boundary in gases is technically challenging. Despite this, when the incident angle is small, light reflection can still occur. This phenomenon is commonly observed in nature: in a mirage, air layers at varying temperature levels can significantly modify the optical path with a Δn of only 1×10^{-5}.[3] By leveraging similar principles, gas-phase refractive elements like lenses,[4] beam samplers,[5] and intracavity acousto-optic loss modulators,[6] as well as gratings using multiple plasma layers,[7] have been constructed.

2. GAS-PHASE ACOUSTO-OPTIC MODULATION

We present efficient acousto-optic modulation of high peak-power near-infrared (1030 nm) pulses using ambient air as the acousto-optic medium.[8] Fig. 1**a** shows a schematic of the experimental setup. Combining highly intense airborne ultrasound, which we achieved using a high-power ultrasonic transducer of 7 cm diameter in an acoustically resonant configuration (see the reflector), we estimate a peak sound pressure level of about 148 dB. The ultrasonic transducer operates at a frequency of $F = 500\,\mathrm{kHz}$. Using the speed of sound in air, $c_\mathrm{s} = 343\,\mathrm{m\,s^{-1}}$, the Bragg angle, corresponding to half the diffraction angle, is

$$\sin\theta_\mathrm{B} = \frac{\lambda F}{2c_\mathrm{s}}, \tag{1}$$

yielding

$$\theta_\mathrm{B} \approx 0.75\,\mathrm{mrad}. \tag{2}$$

By choosing a sufficiently large beam diameter, we reduced the beam's own divergence to be able to separate the diffracted and transmitted beams. The ratio of angular divergence to diffraction angle we reached is $\frac{\theta_\mathrm{B}}{\theta_\mathrm{beam}} \approx 10$. Upon sufficient interaction length, enabled by a multi-pass scheme, the diffraction efficiency exceeded 50 % (see Fig. 1**b**). Our numerical simulations (3+1d split-step Fourier method) show that the diffraction efficiency is limited by the acoustic sound pressure level (SPL, given in dB). Fig. 1**b** shows the measured diffraction efficiency as a function of the SPL for two configurations, with acoustic reflector (Standing) and without (Traveling), demonstrating the much improved diffraction efficiency of the resonant AOM. We estimate that the diffraction efficiency can be increased to above 80 % by increasing the SPL by only about 5 dB to 10 dB.

Our experiments demonstrate that gas-based light control is possible when extremely high sound pressure levels are employed. Prospectively, more gas-based sono-photonic optical elements could be realized, including lenses or wave guides. The difficulty in this approach lies in the small Δn that can be achieved in gases. Our first approach tackled these difficulties using high SPL and long interaction length. An alternative approach is the employment of different gases: The refractive index modulation by pressure modulation p in relation to normal pressure p_0 is approximately given by the modified Edlén equation:[9]

$$\Delta n \propto (n-1)\,\frac{p}{p_0}, \tag{3}$$

which scales with $(n-1)$. Therefore, choosing a gas with higher refractive index may allow for a substantially larger Δn, increasing the diffraction strength.

3. OUTLOOK

Gas-based sono-photonic light control is a promising novel approach to light control in extreme parameter regimes. Hence, we anticipate that this advancement will open up novel parameter domains for AOM technology. It also holds immense potential for a wide range of advanced photonic applications including, but not limited to, optical switches, phase modulators, spectral filters, and dispersion control. Finally, future investigations involving different gases and different sono-photonic interaction geometries may allow for further maturing of this field.

REFERENCES

[1] Fibich, G. and Gaeta, A. L., "Critical power for self-focusing in bulk media and in hollow waveguides," *Optics Letters* **25**, 335 (Mar. 2000).

[2] Kim, S.-H., Yoko, T., and Sakka, S., "Linear and Nonlinear Optical Properties of TeO2 Glass," *Journal of the American Ceramic Society* **76**, 2486–2490 (Oct. 1993).

[3] Ciddor, P. E., "Refractive index of air: new equations for the visible and near infrared," *Applied Optics* **35**, 1566 (Mar. 1996).

[4] Michaelis, M., Dempers, C., Kosch, M., Prause, A., Notcutt, M., Cunningham, P., and Waltham, J., "A gas-lens telescope," *Nature* **353**(6344), 547–548 (1991).

[5] Vandamme, E. and Muys, P., "Ultrasonic beamsplitter for high-power co2 lasers," *Journal of Optics A: Pure and Applied Optics* **3**(4), S68 (2001).

[6] Grulkowski, I., Jankowski, D., and Kwiek, P., "Acousto-optic interaction with the use of cylindrical ultrasonic waves in the laser cavity," *Applied Optics* **48**, C81 (Mar. 2009).

[7] Michine, Y. and Yoneda, H., "Ultra high damage threshold optics for high power lasers," *Communications Physics* **3**(1), 24 (2020).

[8] Schrödel, Y., Hartmann, C., Zheng, J., Lang, T., Steudel, M., Rutsch, M., Salman, S. H., Kellert, M., Pergament, M., Hahn-Jose, T., et al., "Acousto-optic modulation of gigawatt-scale laser pulses in ambient air," *Nature Photonics* , 1–6 (2023).

[9] Edlén, B., "The Refractive Index of Air," *Metrologia* **2**, 71–80 (Apr. 1966).