Design of Novel Optical Cavities for Strong Shock Compression

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Laser-induced strong shock waves with high efficiency remain a technical challenge, evidenced by the effort invested at large-scale national laboratories to optimize the laser-induced shock compression of pellets of light elements. Here, we present theoretical work on designing novel optical cavities for strong shock generation at a tabletop scale. The key idea is to utilize multiple laser pulses spatially and temporally shaped to form concentric laser rings on condensed matter samples. Each laser ring launches a 2D focusing pressure wave that converges at a common central point. The pulses are delayed in the nanosecond range and spaced by microns, matching the laser scanning speed to the shock wave speed, typically several μm/ns in condensed matter, allowing amplification of the pressure waves through superposition. The herein-described optical cavities are expected to maintain or even exceed the shock excitation efficiency of 10⁴ GPa/J reported in our previous work using a single laser ring, where the limiting factor in generating stronger shocks was the saturation of input laser energy. The current design for multiple laser rings bypasses the saturation due to much larger excitation areas; thus, the total input laser energy can be dramatically increased. We further experimentally show that dielectric metasurfaces can combine all optics for forming the required clean high-fluence laser rings in a single optics. Our work provides a viable pathway toward applying laser-induced strong shock compression of condensed matter. The current tabletop scheme caters to the need of the shock compression community by providing the flexibility to test new shock compression strategies.

INTRODUCTION

Shock waves are of fundamental and practical interest to many fields, including materials science¹, physical chemistry²⁻³, astrophysics⁴, medical therapies⁵, and many others. In particular, information regarding high-pressure equations of state can be extracted through the study of shock propagation in condensed matter. In classical laser-shock experiments, shock waves are generated by depositing pulsed laser energy in a planar photoacoustic transducer layer deposited onto a sample. Absorption of the laser energy launches an out-of-plane shock wave traveling into the sample. Commonly in these experiments, the shock wave is interrogated optically after propagation through the material at either a free surface or the interface of a transparent substrate. Such laser-induced shock wave techniques have typically been limited to large laser facilities, where high-energy laser pulses are readily available. Typical laser-shock excitation efficiency, demonstrated at LCLS and the OMEGA laser facilities, ranges from 15 GPa/J to 100 GPa/J⁶⁻⁷.

An alternative route towards shock wave experimentation is homogeneous direct-drive techniques. In these experiments, the sample itself serves as both the test material and shock launching layer by making the material of interest optically absorptive. Absorption of the laser energy leads to thermal expansion or ablation of the material, launching shock waves diverging from the excitation region, traveling laterally in the plane of the sample. This experimental geometry allows for the direct visualization of shock wave propagation and is well-positioned for the application of spectroscopic probes to investigate shock-induced phenomena. Additionally, it allows the experimenter to shape the excitation arbitrarily for varied experimental designs. One such design demonstrated in our previous works¹⁻⁸ is based on 2D focusing of shock waves. A converging shock wave is launched by shaping the laser pulse into a ring, whose pressure amplifies as it reaches the focus. This experimental geometry has been shown to reach excitation efficiencies as high as 10⁴ GPa/J, with pressures of tens of GPa reached with pulse energies as low as a few mJ. This allows one to conduct high-pressure experimentation with a commonplace tabletop laser amplifier system with the capability for rapid rearrangement and high throughput experimentation (hundreds of shots per day).

Herein we present two novel excitation schemes harnessing the fundamental principles of energy focusing and phase matching towards higher shock excitation efficiency. See Ref.¹⁰ for a 1D demonstration of spatial tuning and superposition of multiple acoustic waves excited by an array of laser photoacoustic sources shaped as lines. As demonstrated previously, both techniques are based on the excitation of multiple synchronized laser rings rather than a single ring. The operating principle of this technique is the superposition of multiple converging shock waves. The
first excitation will be the largest ring, with radius $R_0$ at time $T_0$. The second excitation, whose pulse arrives at the sample at time $T_0 + dT$, will have radius $R_0 - U_s(T_0 + dT)$, where $U_s$ is the shock speed, and $dT$ is the inter-pulse time delay. In this way, the second ring shock is excited at the position of the previously launched converging shock that has propagated over distance $U_s dT$. Combining these two excitations will lead to the nonlinear enhancement of the traveling wave pressure. Subsequent $n$-excitations will have timing $T_0 + (n-1)dT$ and radius $R_0 + U_s(T_0 + ndT)$. Harnessing the power of both shock amplification through 2D convergence and acoustic phase matching, one can expect significant increases in the achievable pressures [11].

**FIG. 1.** Design of an axicon cavity to generate successive laser rings on a condensed matter sample. The inset shows a 2D schematic of the axicon cavity, with the axis of symmetry shown by the gray dashed line. The focusing lens is of 700 mm focal length; the axicons are 200 mm in diameter. The concave axicon has an angle of 1.6 degrees, while the convex one has 1.5 degrees. Variable delays between successive laser rings in the ns range are achieved through the variable cavity length of typically 10 mm to 500 mm.

**DESIGN 1: AXICON CAVITY**

The first scheme for multi-ring shock excitation is based around a cavity consisting of two axicons, one concave and one convex (Fig. 1). This design borrows from the principles of the Free-space Angular Chirp Enhanced Delay (FACED) cavity [12, 13]. In the FACED cavity, the input of a focused laser pulse generates a sequence of sub-pulses that emerge spatially and temporally separated. Our axicon cavity is a 3D variation of the FACED cavity with an aperture at the center of the concave axicon, allowing for the input of a focused Gaussian laser pulse. Where the 3D design diverges from the 2D FACED cavity is in the output. In place of a series of spatiotemporally delayed laser spots, with a spatial profile identical to the input, pulses emerge from the axicon cavity as a series of concentric rings, with the largest radius ring arriving first and subsequent smaller radii ring delayed by $\tau$. The beams emerge from the cavity with the $k$-th output beam at angle $\alpha = k|\theta_{concave} - \theta_{convex}|$, where $\theta_{concave}$ and $\theta_{convex}$ are the angles of the concave and convex axicons, respectively. The size of the rings on the sample is defined by the focusing element used in the sample. The delay between subsequent pulses is defined by the relation $\tau = 2d/c$ with delay $\tau$, cavity length $d$, and light speed in the air $c$.

A ray tracing simulation of this cavity output is shown in Fig 2. The simulated camera image shows the output of an axicon cavity, consisting of axicons 200 mm in diameter with angles of 1.6 and 1.5 degrees for the concave and convex axicons, respectively, focused by a $\times10$ microscope objective. This generates a series of four rings, each 10 $\mu m$ smaller than the previous one, with an inter-pulse time delay of 2 ns. The characteristic feature of this cavity is the readily variable temporal spacing, merely varying the spacing between axicons, allowing for one to tune the shock excitation timing for the best pressure enhancement. With the linear superposition of ten 2 mJ rings in water, one can expect to reach pressures as high as 300 GPa [8], with higher pressures expected for nonlinear superposition.
FIG. 2. Ray-tracing simulation of the axicon cavity setup. (A) Detector image at the sample plane. Note that the input beam has a flat-top profile. (B) Temporal laser profile.

This optical design’s drawback is that the high energy input beam is focused inside the cavity, risking laser damage to the axicon mirrors. It is also practically difficult to modify the inter-ring spacing as desired unless the focusing optics before the sample are replaced by a customized metalens array to control each of the individual ring positions and dimensions. In the following, we will show another design based on flat mirrors that do not require focusing optics to split a single input beam into many output beams.

DESIGN 2: TWIN “DEATH STARS”

The second scheme is based around the “death star” cavity, originally used for high-frequency (tens to hundreds of GHz) acoustic wave spectroscopy [14]. The death star operates with a four-mirror cyclic cavity, whose last mirror is a partial reflector (PR). After traveling through the cavity the PR allows part of the laser input pulse to exit the cavity and horizontally offsets the reflected laser beam for another round trip through the cavity. This leads to an output of n-horizontally spaced laser pulses, with temporal delay set by the death star round trip time. In the proposed design, we will utilize two death star cavities connected by a twisted periscope. The first death star generates a horizontal array of n-pulses. The twisted periscope rotates this array by 90 degrees. This vertical array is input into the second death star cavity generating m-pulses from each input. In this way, we can generate an \( n \times m \) array of pulses from an input single Gaussian pulse, see Fig. 3. This array can then be transformed into multiple rings at the sample surface by sequentially passing through either a refractive axicon array or an axicon array phase object [15] and then through focusing optics. Since all the beams transmitted through the axicon array are collinear, a single conventional focusing element can be used to form concentric rings at the sample location. However, any light bypassing the axicons travels along the optical axis and therefore would be focused into a central spot by the focusing element, detrimental to many applications. A solution preventing hot spots entirely is to combine a lens array with an axicon array in a single phase metasurface, as, e.g., in [16]. Such a phase object can directly produce multiple rings at the sample location without the need of any conventional focusing element. Furthermore, this scheme benefits from the high-laser damage threshold of phase masks used to focus or shape high-power laser beams [17–19].

To obtain the spatiotemporal superposition of all the laser-excited ring shock waves, it is possible to either tune the time delay between successive beams or the spatial separation between successive rings. The inter-time delay between successive laser beams can be tuned by changing the death star dimensions of the four-mirror cyclic cavity. Alternatively, tuning the ring radii by changing the axicon array is convenient. Note that the laser intensity of each single laser ring depends on how the PRs composing the Death Star are fragmented – in practice, each PR is composed of many optical windows, laterally shifted such that each beam inside the cavity hits a specific window, with different optical transmission coefficients \( T_n \). For instance, if each of the two partial reflectors PR is spatially fragmented with a change in transmittance that follows,
FIG. 3. Twin Death Star setup to generate multiple laser rings, unifying additive-boosting and energy-focusing strategies for shock enhancement. Note that the input laser beam is 2.5 mm in diameter, the cavity mirrors are 4 inch (square shape) in length, and the axicon array consists of $5 \times 5$ axicons with an overall dimension of 50 mm $\times$ 50 mm. Labels, AA: axicon array, PR: partial reflector.

$$T_n = T_1, \ T_1/(1-T_1), \ T_1/(1-2T_1), ..., \ T_1/(1-(n-1)T_1),$$  \hspace{1cm} (1)

where $T_1$ is the optical transmittance for the first pulse arriving on the partial reflector, then the intensity of each beam that exits the twin Death Star is identical, as displayed in Fig. 3(A). To limit losses on the last beam circulating the Death-Star cavity, the last transmission coefficient $T_n$ should be 100%, which gives from Eq. (1) the extra condition on $T_1$, which is $T_1/(1-(n-1)T_1) = 1$.

The Death Star setup’s simulated and measured laser beam profiles are presented in Fig. 3. With an inter-time delay between pulses set to 2 ns, the twin Death Stars generate a $5 \times 5$ array of laser dots as sketched Fig. 3(A), front panel. After passing through an axicon array made of diffractive metasurfaces or refractive axicons (back panel), multiple concentric beams are formed at the focus of a 10× objective lens of 20 mm focal length. The axicon angles $\theta_n$ vary from $\theta_1 = 0.05^\circ$ to $\theta_{25} = 1.25^\circ$ in 0.05$^\circ$ steps.

To show that modern metasurfaces are a viable way for implementing this novel scheme for laser-inducing shock waves, we present an experimentally measured metasurface-generated laser ring in Fig. 3(B): the metasurface consists of 600 nm high circular titanium dioxide nanopillars arranged on a square 350 nm grid. As this grid size is considerably smaller than the 532 nm operation wavelength, the metasurface only shapes the phase of the fundamental transmitted beam and creates no higher diffractive orders. By varying the nanopillar diameter, we emulate a digitized phase profile that combines the effect of a 0.5$^\circ$ axicon and a 10× objective lens. The result is a clean 200 µm laser ring in the sample plane, without visible hot spot (see above and Fig. 3B)). Furthermore, to be able to induce strong shock waves, the metasurface must be able to sustain high laser fluences. As the metasurface is manufactured only of dielectric materials, our investigations show no damage up to a fluence of 1.1 J/cm$^2$; higher than many metallic mirrors. As metasurfaces can today be manufactured on the wafer scale [20], a full metasurface axicon and lens array can be implemented in a single process. This eliminates the need for assembly at a later stage and provides a relative alignment of the array elements on the nanometer level.
The conjunction of an axicon array and the objective lens can generate multiple concentric rings with ring radii $r_n = 220 - 10(n - 1)$ µm and constant ring width of 3 µm, see Fig. 4(C). Note that since each beam from the twin Death Star has equal intensity, the laser fluence of the rings in this example increases as $1/r_n$ – the ring surface is proportional to $r_n$. As mentioned above, it is possible to obtain any desired fluence distribution of the rings by adjusting the transmission coefficients $T_n$ in Eq. (1).

The laser scanning speed in the simulation is 5 µm/ns, see Fig. 4(D), which is in range of the acoustic speed of many solid materials. A different set of focusing optics, axicon angles, and Death Star inter-time delay can be calculated to obtain a different laser scanning speed for varied samples. Owing to the nonlinear propagation of shock waves that imposes the shock speed to vary drastically with shock pressure, it is imperative to account for the nonlinear propagation of the shock waves in the sample. At very high laser energies and corresponding shock pressures, the laser scanning speed should not be constant anymore but should increase to follow the build-up of the shock wave.

**SUMMARY AND OUTLOOK**

We have presented two novel laser cavity designs for generating a concentric laser ring pattern with variable ring radii and time delay. This experimental design will allow studying strong shock waves in condensed matter through the excitation and superposition of multiple 2D converging shock waves. Owing to their compact geometry, these setups are suitable for benchtop experiments, which are the natural next steps. From our previous experiments with a single-ring shock in water, we have observed shock excitation efficiencies as high as $10^4$ GPa/J [8]. When extended to multiple rings, we expect increased efficiency due to the constructive interference of the nonlinear shock waves. This experimental technique has implications in various fields where high-pressure excitation is of paramount importance.
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