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Leveraging ±1st-order Bragg diffraction synergy for bandwidth enhancement and frequency downshift in acousto-optic modulators

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Acousto-optic modulator (AOM), serving as core components in optical measurement systems such as distributed optical fiber sensing (DOFS), plays a crucial role in achieving intensity, frequency, and phase modulation [1–3]. Its tunable bandwidth is a key parameter determining system performance, including spatial resolution, noise immunity, and so on [4]. However, because AOM achieves frequency modulation through the linear relationship between the output deflection angle of the +1st or −1st-order diffracted light and the driving frequency, their bandwidth is constrained by the coupling efficiency of collimators and focusing optics, as well as the physical characteristics of the acousto-optic crystals. This limitation makes it challenging to further enhance the bandwidth, thereby restricting the information capacity of the system [5, 6]. Furthermore, in coherent detection optical systems, the bandwidth at the detection end limits the maximum usable frequency shift of the modulator. Thus, maintaining a low intermediate frequency (IF) while simultaneously increasing the tunable bandwidth remains a critical challenge.

This study proposes a novel acousto-optic modulator architecture and modulation method based on the synergistic ±1st-order Bragg diffraction modulation to achieve both bandwidth extension and IF downshift. Two AOMs, respectively outputting +1st and −1st-order diffraction, are cascaded to accumulate positive and negative frequency shifts. A mirror enables secondary modulation, doubling the frequency shift magnitude. Crucially, the two AOMs and the mirror are coupled via free space, thereby circumventing the bandwidth limitations imposed by the coupling angle constraints of focusing optics. Furthermore, the driving frequencies applied to the two AOMs satisfy a complementary constraint relationship, ensuring complete optical path reversibility. Experimental results demonstrate that the proposed diffraction synergy AOM (DS-AOM) yielded a significantly enhanced 3-dB bandwidth of 266 MHz—corresponding to 4.4 times that of traditional collimator-focusing structures—while achieving a down-shifted IF band covering the range from 1 to 400 MHz, which makes it promising for widespread adoption as a next-generation commercial product in fields such as DOFS.

Principle and fabrication. The schematic diagram of the DS-AOM architecture is illustrated in Figure A1. Continuous light $\boldsymbol{a}$ enters the AOM via an optical circulator. Radio frequency (RF) signals $RF_1(t)$ and $RF_2(t)$ drive piezoelectric transducers (PZTs) to generate acoustic waves within AOM1 and AOM2, respectively, inducing refractive index gratings. The direction of acoustic wave propagation is indicated by the arrows. Subsequently, the incident light $\boldsymbol{a}$, collimated by a collimator, enters AOM1 at an incidence angle θ_{i1} satisfying Eq. (A1). Since the direction of incidence is opposite to the direction of acoustic wave propagation within AOM1, energy conservation dictates that the incident light absorbs phonon energy. Consequently, AOM1 outputs +1st-order diffracted light $\boldsymbol{b}$ with an up-shifted frequency. The deflection angle θ_{d1} satisfies Eq. (A2). In conventional fiber-coupled AOMs, the output beam $\boldsymbol{b}$ is coupled into an optical fiber via focusing optics. However, due to constrained coupling angles, the tunable bandwidth is inherently limited. In contrast, within the DS-AOM architecture, the output light $\boldsymbol{b}$ propagates in free space, serving as the input to AOM2. This configuration eliminates the bandwidth constraint imposed by fiber coupling angles. Crucially, AOM2 is rotated by a specific angle such that the direction of light incidence becomes identical to the direction of acoustic wave propagation within AOM2. Consequently, the light transfers energy to the phonons. Therefore, AOM2 outputs −1st-order diffracted light $\boldsymbol{c}$ with a down-shifted frequency. The output deflection angle $\theta_{d2}(t)$ satisfies Eq. (A3). Subsequently, $\boldsymbol{c}$ output from AOM2 impinges perpendicularly onto a fixed mirror and retraces its path, undergoing secondary modulation successively by AOM2 and then AOM1. Leveraging the inherent reversibility of the Bragg diffraction process, the light experiences identical modulation effects during its forward and backward propagation. Consequently, the magnitude of the cumulative frequency shift is doubled. To ensure the −1st-order diffracted light $\boldsymbol{c}$ always impinges perpendicularly onto the

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mirror surface, the driving frequencies $f_{RF1}(t)$ and $f_{RF2}(t)$ applied to AOM1 and AOM2 must satisfy the constraint relationship of Eq. (A4). That is, the sum of the driving frequencies of the two AOMs equals a constant F. The physical significance of this constraint is demonstrated in Appendix A.

Figure B1 illustrates the frequency modulation process of the DS-AOM, and the detail is illustrated in Appendix B. As a result, the tunable bandwidth of the DS-AOM can reach twice the sum of the individual AOMs' tunable bandwidths in theory. Furthermore, when the condition $f_{1,min} = f_{2,max}$ is satisfied, the frequency shift can be continuously tuned starting from zero.

The fabrication detail of the DS-AOM is illustrated in Appendix C. Both AOM1 and AOM2 utilize tellurium dioxide (TeO_2) crystals, with designed center frequencies of 280 and 180 MHz, respectively. The AOM is compactly packaged within a metal housing measuring 80 mm× 43 mm× 20 mm as shown in Figure C1, featuring single mode fiber input/output ports and RF1/RF2 radio frequency interfaces. Figures A1 and C1 depict the identical system viewed from opposite sides (front vs. back), maintaining equivalent physical significance.

Experimental setup and results. Figure D1 depicts the coherent detection experimental setup designed for characterizing the IF signal modulated by the DS-AOM. The frequency response characteristics of AOMs can be efficiently characterized by modulating and detecting stepped frequency pulses, the detail is illustrated in Appendix D. As shown in Figure D2, the DS-AOM achieves an output frequency band covering the 1–400 MHz range, consistent with the theoretical calculations. The measured 3-dB bandwidth of the DS-AOM is 266 MHz, whereas the conventional AOMs exhibit 3-dB bandwidths of only 60 MHz each. Therefore, compared to the conventional architecture, this study achieves a 4.4-fold enhancement in the 3-dB bandwidth.

To characterize the transient response of the DS-AOM, the driving frequencies were set to $f_{RF1} = 280$ MHz and $f_{RF2} = 180$ MHz with a pulse width of 200 ns, generating an optical pulse shifted by 200 MHz. The amplitude envelope of the pulse was extracted via Hilbert transform followed by absolute value acquisition. As shown in Figure D2(b), the full width at half maximum (FWHM) of the pulse was measured to be approximately 140 ns, with the average rise and fall times of the optical pulse being 43 ns. This measured transient response establishes a fundamental limit on the minimum achievable pulse width of diffraction synergy AOM. To characterize the frequency-sweeping performance of the DS-AOM, the AWG generated complementary linear-swept signals. The sweep ranges for $RF_1(t)$ and $RF_2(t)$ spanned 230–330 MHz and 130–230 MHz, respectively, with a sweep duration of 1 ms. The STFT spectrogram of the driving signals and beat signal are shown in Figures D2(c) and (d), respectively. Figure D2(c) superimposes the spectrogram of $RF_1(t)$ and $RF_2(t)$ to visualize their constrained relationship. Evidently, $RF_1(t)$ exhibits a linearly increasing frequency sweep with a positive chirp rate of $Slope_1 = 10$ THz/s; $RF_2(t)$ shows a linearly decreasing frequency sweep with a negative chirp rate of $Slope_2 = -10$ THz/s; their instantaneous frequency sum always remains constant at 460 MHz, rigorously satisfying the complementary constraint of Eq. (A4). The beat signal spectrogram in Figure D2(d) reveals a chirp rate of 40 THz/s—four times that of the individual drive signals—while maintaining the original 1 ms pulse duration. The quadrupled chirp rate directly enables a fourfold sweep bandwidth enhancement in the DS-AOM through effective chirp rate amplification.

With the source power set to 0 dBm and the AOM maintained in the off state, the measured output power was −40.0 dBm, yielding an extinction ratio of 40 dB for the DS-AOM. Subsequently, the AWG was configured to output continuous RF signals with $f_{RF1} = 280$ MHz and $f_{RF2} = 180$ MHz, generating a 200 MHz frequency-shifted continuous-wave optical output. The measured output power under this condition was −6.2 dBm, indicating an insertion loss of approximately 6 dB at the 200 MHz center frequency. Based on this insertion loss value and the characterization data presented in Figure D2(a), insertion loss values at other frequencies can be extrapolated.

Conclusion. This work proposes a novel DS-AOM architecture based on ±1st-order Bragg diffraction synergy, overcoming the technical bottleneck in traditional AOMs where bandwidth extension and frequency band downshift cannot be simultaneously achieved. Additive positive/negative frequency shifting is achieved by synergistically cascading two AOMs that respectively output +1st and −1st order diffracted light, and the free-space optical coupling design circumvents conventional fiber-coupling angular constraints. The combined use of complementary RF signals and a mirror enables a reversible optical path and double-pass modulation, theoretically yielding a total bandwidth twice the sum of the individual AOMs' bandwidths. Experimentally, the DS-AOM achieves a 3-dB bandwidth of 266 MHz—representing a 4.4-fold enhancement over the 60 MHz bandwidth of conventional architecture—while covering a frequency band of 1–400 MHz. This solution provides a high-performance frequency modulation platform offering scalability, integrability, and strong application potential for DOFS.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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