A New View on Acousto-optic Laser Beam Combining

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Abstract: Coherent combining is a well-known principle of up-scaling the peak power in different types of pulsed lasers. A new type of acousto-optic beam combiner for pulsed lasers is proposed and discussed. We demonstrate that phase delay between two laser beams can be controlled and the beams can be combined using one acousto-optic device. Two cases of degenerate and non-degenerate Bragg diffraction are analyzed and compared. The experiment with anisotropic Bragg diffraction in paratellurite demonstrated efficiency of combining exceeding 95 %.

1 INTRODUCTION

The principle of coherent combining of laser pulses underlies the creation of ultrahigh-intensity laser facilities (S.N. Bagayev et al., 2014) and the formation of sub-cycle ultrashort optical wave packets (C. Manzoni et al., 2015). One can also use coherently combined pulses for secure free-space communication (G.S. Rogozhnikov et al., 2018). Adding electrical field from several independent sources requires the simultaneous fulfillment of the following conditions:

1. Synchronization of sources with a common frequency standard;
2. Carrier-to-envelope phase stabilization of each source;
3. Correction of phase delays of each channel arising during transport and amplification of beams.

To fulfill the second condition, extra-cavity acousto-optic (AO) modulators are used in the phase feedback system (C. Grebing et al., 2009; B. Borchers et al., 2011; F. Lücking et al., 2012; N.A. Koliada et al., 2016). Often, one master oscillator is used seeding the pulses that are divided into several independently amplified channels and recombined at the output of the amplifiers in front of the compressor (A. Klenke et al., 2013). This ensures mutual coherence of all channels.

Two types of coherent combining systems are distinguished: those with a tiled aperture (S.N. Bagayev et al., 2014; V.E. Leshchenko et al., 2015) and with a commmon aperture (O. Schmidt et al., 2009; A. Klenke et al., 2013; C. Manzoni et al., 2015). The beam combining scheme with a tiled architecture is constructed on an bunch of independent beams each focused onto a target located in the focal plane. To improve the quality of field distribution in focus, adaptive optics systems (F. Li et al., 2017) can be additionally used in such a system.

To combine the beams in a common aperture, polarization (A. Klenke et al., 2013), interference (T.Y. Fan, 2005), or diffraction elements (S.M. Redmond et al., 2012) are used. Systems based on polarization and interference combining elements usually have two inputs and one output beam. Combining of a larger number of beams is achieved by cascading. The spectral addition (O. Schmidt et al., 2009; C. Manzoni et al., 2015) is a special case to be considered separately. In this case, the radiation spectrum expands, which reduces the Fourier-transform-limited duration of the ultrashort pulse. Coherent combining of ultrashort laser pulses directly during AO interac-

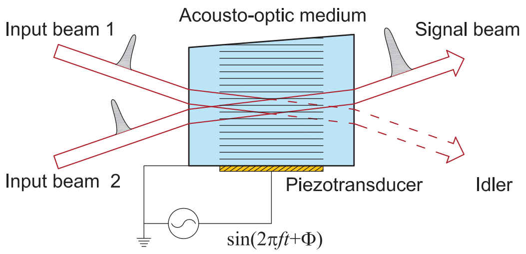

Figure 1: General scheme of an acousto-optic coherent laser pulse combiner.

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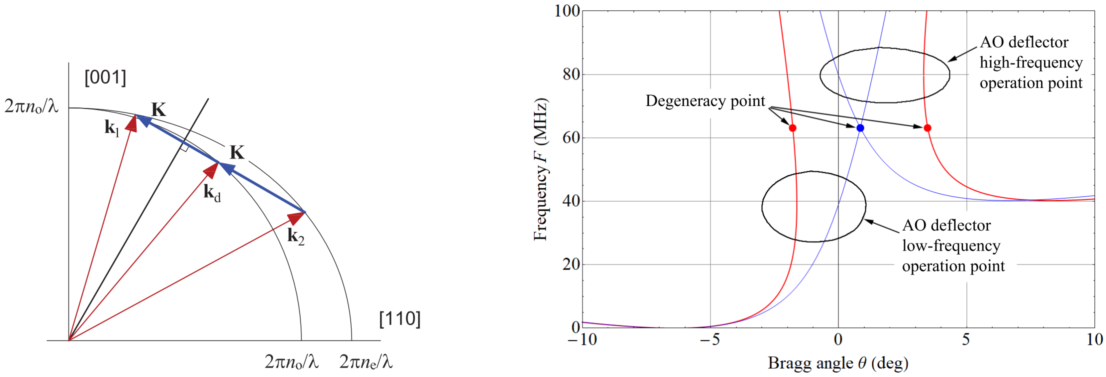

(a) (b)

Figure 2: Wave vector diagram (a) and frequency-angle characteristic (b) of degenerate off-axis anisotropic diffraction in paratellurite.

tion has not been previously considered. The paper considers the design and application features of AO coherent combiner (AOCC) of laser pulses.

2 SYSTEM ANALYSIS

2.1 Degenerate Double Bragg Diffraction

Anisotropic Bragg acousto-optic interaction allows one to obtain high diffraction efficiency of a single beam at the level of 95–99 % (L.N. Magdich et al., 2009; J.-C. Kastelik et al., 2009; J.-C. Kastelik et al., 2018) in one diffraction order. All previously known coherent combining systems require the use of additional phase modulators for fine tuning the phases of interfering beams. In any acousto-optic device the phase adjustment can be carried out directly as a result of diffraction, since the coupled beams belong to different diffraction orders, for example, $+1$ and -1 (V.B. Voloshinov and K.B. Yushkov, 2007), and the phase of the acoustic signal changes phases differently for each of diffraction orders. Thus, it is possible to reduce the number of optical elements in the coherent combining system: one acousto-optic devive instead of two optical elements (phase modulator and beam splitter).

Double Bragg diffraction in anisotropic case is a degenerate type of diffraction that takes place when phase matching condition is simultaneously satisfied for three optical waves, two of them belonging to the slow eigenmode and one belonging to the fast eigenmode (V.B. Voloshinov and A.Yu. Tchernyatin, 2000). The degenerate AO Bragg diffraction is illustrated in Fig. 2. There are also two tangential AO diffraction points: one at a positive Bragg angle and higher frequency, and another an a negative Bragg angle and lower frequency of ultrasound. Those operation points are used in AO deflectors (A. Goutzoulis and D. Pape, 1994). For the degenerate Bragg diffraction there exists coupling between 0 and ±2 diffraction orders resulting intensity beatings at double ultrasound frequency. For continuous wave beams, average intensity is distributed more or less equally between the diffraction orders at high diffraction efficiency (V.B. Voloshinov and K.B. Yushkov, 2007). However, when one consider pulses laser radiation, the beatings between the diffraction orders can be synchronized with the pulse train to reach the peak of the beatings when the laser pulse arrives.

To describe the operation of the system we use the first-order coupled wave theory (A. Yariv and P. Yeh, 1984). The equations of coupled modes for double Bragg scattering have the form:

$$\begin{cases} \dfrac{dA_0}{dz} = -\dfrac{q}{2}A_1(z)\exp(i\Phi); \\ \dfrac{dA_1}{dz} = \dfrac{q}{2}A_0(z)\exp(-i\Phi) - \dfrac{q}{2}A_2(z)\exp(i\Phi); \\ \dfrac{dA_2}{dz} = \dfrac{q}{2}A_1(z)\exp(-i\Phi), \end{cases} \tag{1}$$

The solution for one input beam with initial conditions $A_0(0) = 1, A_1(0) = A_2(0) = 0$ is well known:

$$\begin{cases} A_0(z) = \cos^2\dfrac{qz}{2\sqrt{2}}; \\ A_1(z) = \dfrac{\exp(i\Phi)}{\sqrt{2}}\sin\dfrac{qz}{\sqrt{2}}; \\ A_2(z) = \exp(2i\Phi)\sin^2\dfrac{qz}{2\sqrt{2}}. \end{cases} \tag{2}$$

In the presence of two incident waves with the same optical frequency the initial conditions for complex amplitudes must be written as:

$$\begin{cases} A_0(0) = 1; \\ A_1(0) = 0; \\ A_2(0) = \exp(-2i\Omega t), \end{cases} \tag{3}$$

since complex field representation in slowly-varying envelope approximation (SVEA) already includes Doppler shifts between the diffraction orders (V.N. Parygin and L.E. Chirkov, 1975). The solution of Eqs. (1) with initial conditions (3) explicitly describes the beatings:

$$A_0(L) = \exp(-i\Omega t + i\Phi)\left[\cos(\Omega t - \Phi) + i\cos\frac{qL}{\sqrt{2}}\sin(\Omega t - \Phi)\right]; \tag{4}$$

$$A_1(L) = \sqrt{2}\, i \exp(-i\Omega t)\sin\frac{qL}{\sqrt{2}}\sin(\Omega t - \Phi); \tag{5}$$

$$A_2(L) = \exp(-i\Omega t - i\Phi)\left[\cos(\Omega t - \Phi) - i\cos\frac{qL}{\sqrt{2}}\sin(\Omega t - \Phi)\right]. \tag{6}$$

The intensities of the diffraction orders $I_p = |A_p|^2$ are respectively equal to:

$$I_0 = I_2 = \cos^2(\Omega t - \Phi) + \sin^2(\Omega t - \Phi)\cos^2\frac{qL}{\sqrt{2}}; \tag{7}$$

$$I_1 = 2\sin^2(\Omega t - \Phi)\sin^2\frac{qL}{\sqrt{2}}. \tag{8}$$

The maximum of the diffraction efficiency in the first order takes place at $qL = \pi/\sqrt{2}$ and $\Omega t - \Phi = \pi$, and the sum of the input beam intensities is $I_1 = I_0(0) + I_2(0)$. Since there is no diffracted beam in the first order when the driving radio-frequency (RF) signal is switched off, this device can be also used as a pulse picker or modulator (E.I. Gacheva et al., 2017).

2.2 Non-degenerate Bragg Diffraction

The addition of two beams can also be obtained using a single Bragg diffraction without degeneracy. In this case, the equations of coupled modes have the form

$$\begin{cases} \dfrac{dA_0}{dz} = -\dfrac{q}{2}A_1(z)\exp(i\Phi); \\ \dfrac{dA_1}{dz} = \dfrac{q}{2}A_0(z)\exp(-i\Phi), \end{cases} \tag{9}$$

with the initial conditions:

$$\begin{cases} A_0(0) = 1; \\ A_1(0) = \exp(-i\Omega t), \end{cases} \tag{10}$$

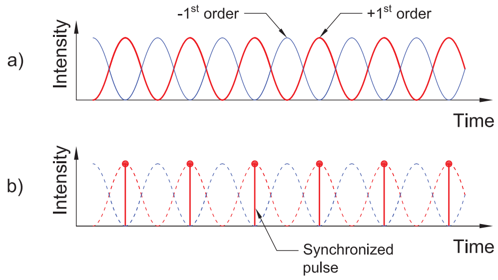

Figure 3: Light intensity of diffracted beams: (a) beatings for continuous-wave radiation; (b) combining of a synchronized pulse train.

The solution of the system of equations has the form:

$$A_0(L) = \cos\frac{qL}{2} + \exp(-i\Omega t + i\Phi)\sin\frac{qL}{2}; \tag{11}$$

$$A_1(L) = \exp(-i\Omega t)\cos\frac{qL}{2} - \exp(-i\Phi)\sin\frac{qL}{2}, \tag{12}$$

and the intensities are equal to:

$$\begin{cases} I_0 = 1 + \sin(qL)\cos(\Omega t - \Phi); \\ I_1 = 1 - \sin(qL)\cos(\Omega t - \Phi); \end{cases} \tag{13}$$

Such a diffraction geometry has an advantage over the twofold degenerate geometry considered above, since the maximum intensity in each of the diffraction orders is achieved at $qL = \pi/2$, that is, at half the power of the controlling RF signal compared to a degenerate geometry and four times less power in compared to diffraction of a single input beam with maximum efficiency. Moreover, such a configuration allows one to choose different frequencies of AO interaction, in contrast to degenerate geometry, whose frequency is uniquely determined by the propagation direction of the acoustic wave in the AO crystal α and the wavelength of light λ. Typical ultrasound frequencies in paratellurite are between 20 and 150 MHz with up to an octave-spanning bandwidth limited by electrical impedance matching of the piezoelectric transducer (V.Ya. Molchanov and O.Yu. Makarov, 1999). Note that the tangential geometry of AO interaction supports wide optical bandwidth exceeding 100 nm in the visible wavelength region (A. Dieulangard et al., 2015) that is enough for providing high diffraction efficiency of ultrashort laser pulses. Non-degenerate diffraction can be obtained both for isotropic and for anisotropic AO diffraction that broadens the choice of acousto-optic materials. In the case of isotropic diffraction, there will be no group mismatch between zero and first order, which reduces the diffraction efficiency of ultrashort laser pulses (K.B. Yushkov and V.Ya. Molchanov, 2011).

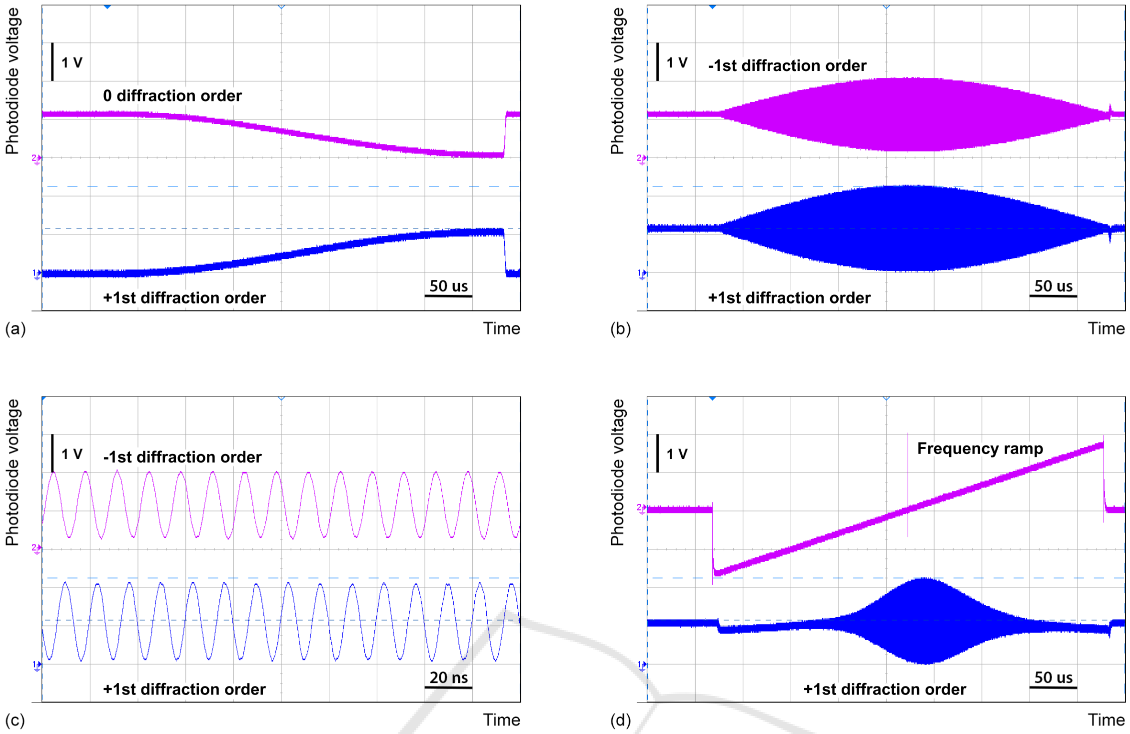

Figure 4: Oscilloscope traces of coherently combined laser beams: (a) intensity of zero and first diffraction orders at a single input of the beam in the mode of linear amplitude variation; (b) the intensity of the zero and first diffraction orders for two input beams in the mode of linear amplitude ramp mode; (c) intensity beats in two output beams; (d) diffraction intensity in the frequency sweep mode in the range ±2 MHz. Scale bars indicate the measurement units along coordinate axes.

3 EXPERIMENT

The experiment was performed with AOCC based on paratellurite single crystal with orientation angle $\alpha = 6.4^\circ$ in (110) plane at the laser wavelength of $\lambda = 1053$ nm. The degeneration frequency is 63.5 MHz for this configuration (see Fig. 2b). In the experiment, non-degenerate diffraction at a frequency of $f = 75$ MHz was studied. The single continuous wave laser beam was split into two arxms and each arm was aligned to satisfy Bragg phase matching condition independently from another. The radiation intensity was simultaneously recorded by two photodiodes in both output diffraction orders. The results are shown in Fig. 4. Figures 4 (a) and (b) correspond to linear amplitude ramp of the RF signal. Figure 4 (c) demonstrates counter-phase beatings in each of the diffracted beams with more than 95 % of peak efficiency for each of the output beams. The bandwidth of diffraction demonstrated in Figure 4 (d) using the frequency swept RF signal. As follows from the solution of the coupled mode equations (13), the maximum beat amplitude is achieved when the RF signal amplitude is half that required to achieve maximum efficiency in the diffraction of one of the beams. Moreover, the intensity at the maximum of the beats is approximately 96 % of the total intensity of the two input beams.

4 CONCLUSIONS

Efficient coherent combining of continuous radiation in the considered acousto-optic system is impossible, since the beatings with the ultrasound frequency occur between the diffraction orders, and the average time intensity in each order is approximately 1/2 of the total for non-degenerate geometry and 1/3 of the total for degenerate geometry (V.B. Voloshinov and K.B. Yushkov, 2007). This limitation can be circumvented if one laser beam is first decomposed into several components using a similar acousto-optic cell (S.N. Antonov et al., 2007). In this case, the beams already have shifted frequencies and it is possible to recombine them at the output obtaining larger part of the total energy in one of the orders.

In practice, combining of pulsed laser beams is of great interest since it allows to achieve much higher peak laser power than in continuous wave mode. If the frequency of the Doppler shift is equal to the intermode interval of the optical spectrum, the beat period coincides with the interval between two adjacent pulses. Thus, one can achieve the intensity of the idler beam to be equal to zero at all times. A similar approach is used, for example, for stabilized AO-modulation of ultrashort pulses (O. de Vries et al., 2015).

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