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Modern applications of high frequency acoustooptics

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The milestone applications of high frequency acoustooptics are discussed. The acoustooptical (AO) components such as Bragg modulator (including standing and running wave modulators), deflectors, others on very high frequencies (up to 10 GHz) working in wide frequency range (up to 3 GHz) are considered. Some review of traditional and modern uses is given. The main principles and peculiarities of Bragg cells design are discussed. The results of experimental investigation appear to correspond with theoretical predictions. The specific problems which are stipulated by a very high frequency range are considered. These are: great influence of sound attenuation; peculiarities of interaction geometry and light aperture formation; multilayer transducer features; electrical matching with electromagnetic power wave guide. The ways of optimizing the parameters of high frequency Bragg cells are discussed.

Keywords: high frequency acoustooptics, acoustooptical interaction, light diffraction, piezotransducer, matching, deflector, modulator, filter, holographic display.

1. Introduction

In spite of a wide range of present-day use of acoustooptical (AO) elements there remains a big temptation to find new applications of acoustooptics due to its unique potential applicabilities in various domains of informational signal processing. This especially concerns high frequency acoustooptics, which attracts attention due to the possibilities of increasing the speed, bandwidth, spatial and time resolution of processed signals.

The main problem, which restricts the shifting to higher frequencies, is the big sound attenuation in known materials, for acoustooptical use. There are also some problems such as electrical and acoustical matching of piezoelectric transducer with electromagnetic power waveguide and sound conductor, reduction of relative AO frequency band due to the lessening of the sound beam divergence, peculiarities of AO interaction geometry, *etc*. In the present work, we decided to address some specific questions when creating high frequency AO components and besides to discuss possible new applications of high frequency acoustooptics.

2. Matching, sound attenuation and interaction geometry

When enhancing the working frequency of AO cell it is very important to find an optimised interaction geometry so as to reduce as much as possible the attenuation of sound waves. Figure 1 illustrates the possible variant of optimised interaction geometry. The acoustic wave is generated by anti-phase multielement transducer that has two-petal directivity diagram; one petal is used for light diffraction while the another is parasitic. The window for incident light is inclined relative to transducer's plane normal to double Bragg angle at central working frequency. Two advantages can be gained in this way: i) the input light reflections can be minimized; ii) the interaction area can be moved very close to the transducer that allows the influence of the sound attenuation to be minimized.

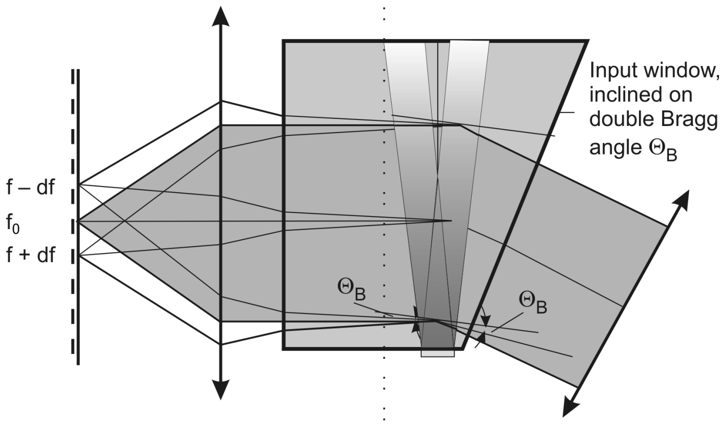

Fig. 1. AO interaction geometry with sound beam generated by anti-phased multielement transducer.

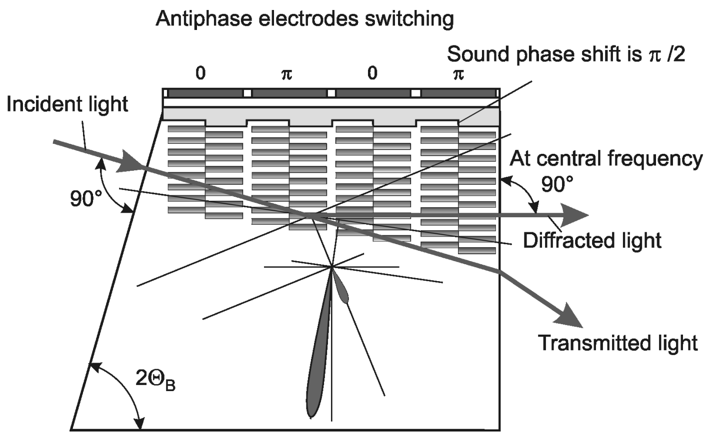

Fig. 2. Light interaction with one-petal sound beam generated by anti-phase array with additional phase shift.

The next step to enhance the efficiency of high frequency Bragg cells is to optimise the sound energy distribution (see Fig. 2). Combining the electrical and acoustical phase shifting variations it is possible to concentrate about 80% of sound energy in one petal of transducer's directivity diagram [1].

Additional enhancement can be reached by electronic control of periodicity of electro-acoustical transducer so as to enlarge the frequency band. Applying specified

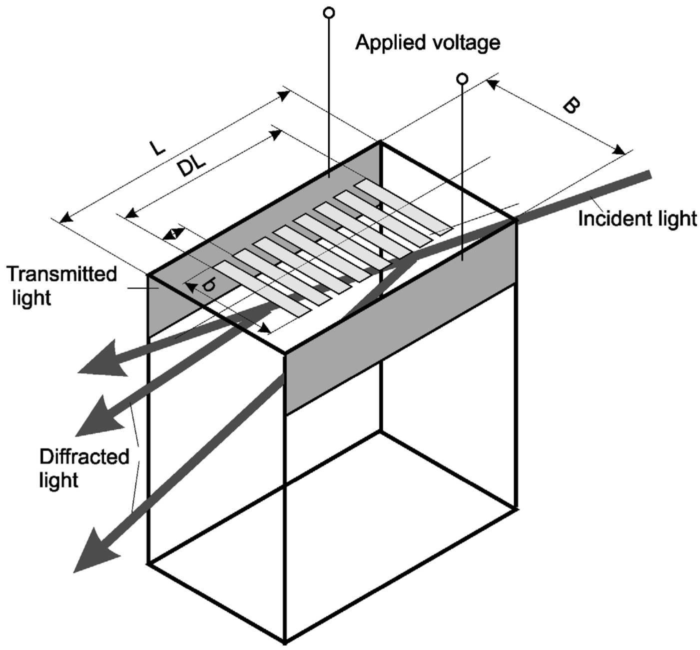

Fig. 3. AO cell with electronically tunable multielement array periodicity.

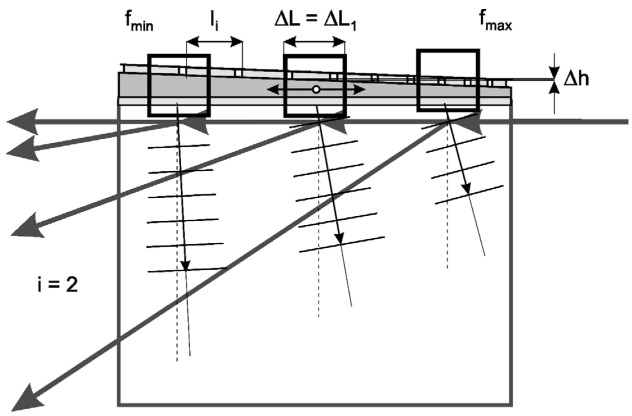

Fig. 4. Moving window multielement transducer system for Bragg angle and resonant frequency automatic tuning.

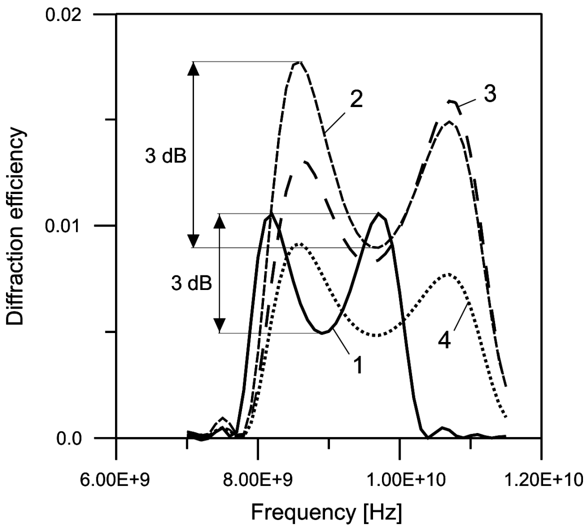

Fig. 5. Diffraction efficiency frequency dependences when different types of multielement transducers are used (curve 1 – in-phase system with constant step of array; curves 2, 3 – variable step arrays with exponential and linear electric power distribution; curve 4 – variable step and constant electrical power).

voltage to additional electrodes (see Fig. 3) deposited at the side faces of piezoelectric soundconductor it is possible to change, due to back piezoeffect, the periodicity of multielement transducer and to enlarge the AO bandwidth [2].

The next step in improving the characteristics of high-frequency AO devices is the use of autotuning system that simultaneously allows: i) electrical matching in a wide frequency range; ii) beam steering to ensure the Bragg synchronization; iii) correction of required thickness of piezolayer and step of multielement array in a wide frequency range by automatic moving of piezotransducer active area. Such an approach can be called the “moving window model” [3]. The system under consideration is sketched in Fig. 4. Figure 5 illustrates how the diffraction efficiency and frequency band could be enhanced by applying such a system (curves 2 and 3) compared to usual in-phase sound excitation system (curve 1).

3. Some applications of high frequency acoustooptics

3.1. High frequency AO deflectors

In order to obtain the largest possible absolute frequency band of a signal processing device, the enlarging of central frequency is reasonable. At the moment due to some natural problems the upper frequency of AO deflectors produced for market does not exceed 3 GHz. At the same time there are many tasks, *e.g.*, radar applications, in which the use of real time AO processing is desired at very high frequencies. In our recent works we showed the possibilities of building the AO deflectors with very high central frequency (up to 10 GHz) and very wide bandwidth (up to 3 GHz) [4]. Now we pay attention to some peculiarities when creating very high frequency deflectors. We consider in the present paper the AO devices based mainly on isotropic Bragg diffraction when sound beam is excited by multielement transducers for extending the frequency bandwidth. The anisotropic diffraction is also used for high frequency AO interaction but it has some restrictions of upper frequency due to the features of materials available today. The choice of multielement transducer type, for the widening of frequency band, depends mainly on the required central frequency. Say, at frequencies about 1 GHz the filter-type multielement transducers are preferable, as they allow providing good electrical matching according to equivalent scheme and planar architecture of filter's cell. At frequencies of about 10 GHz the electrical separation to unique elements drastically enlarges electrical losses. The best solution in this case is to use the acoustical separation of unique elements providing the necessary phase shift between neighbouring elements. The electrical matching in this case can be provided by application of smooth or step-type transformers of electrical impedance. Owing to the acoustical matching of the transducer's layers with elasto-optical medium the theoretically predicted relationships between acoustical impedances as well as between the thicknesses of layers are fulfilled.

3.2. AO high frequency standing wave modulators

Acoustooptical modulator of light diffracted on standing sound waves has found some specific applications such as laser mode synchronisation, fluorometry light modulation and others [5]. The main advantage of AO standing wave modulator consists in the possibility of obtaining a 100% light modulation. Of course, one can speak about 100% light modulation just in the case when attenuation of sound can be neglected [6]. Such a device can be designed at low frequencies, not higher than about one hundred megahertz where sound attenuation in some materials is still not very big. The optical beam must then be directed close to the free end of acoustical resonator, so as to decrease the influence of sound wave attenuation. But at higher frequencies the sound attenuation become big enough and sound amplitude degradation leads to a difference between the amplitudes of opposite direction sound waves, which form the acoustical standing wave. And as a sequence the modulation index is drastically decreased.

Nevertheless, in some tasks (for example, for light modulation in manufacturing the image recognition robots) it is very attractive to have high frequency light modulator with a 100% modulation coefficient.

In our laboratory, an AO standing wave modulator was designed (see photo in Fig. 6) with central frequency 5 GHz and modulation index close to 100% [7]. To overcome the aforementioned problem the acoustical standing wave was formed by two sound waves generated by two, separate electro-acoustical transducers which were placed on opposite butt-ends of acoustical resonator. The 5 GHz electrical signal from

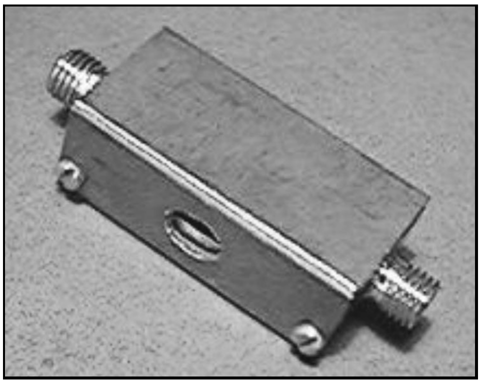

Fig. 6. AO standing wave modulator with central frequency of 5 GHz.

generator output after amplification was separated into two signals, the amplitudes of which could be tuned with separate attenuators. Such an approach allowed building a device in which the acoustical standing wave is situated in the middle of a crystal and can be easily reached by an optical beam to be modulated. AO standing wave modulator designed for 5 GHz showed good accordance to theoretical predictions.

3.3. Integrated collinear AO tunable mirror

The application of collinear anisotropic diffraction allows building a tunable mirror for semiconductor lasers and telecommunication applications, as sketched in Fig. 7. The integrated optical waveguide is created in certain orientation lithium niobate substrate where the refractive indexes for ordinary and extraordinary light are correspondingly $n_o = 2.218$, $n_e = 2.137$. The phase synchronization will proceed at frequency $f = (V/\lambda)(n_o - n_e)$, where V – the velocity of sound wave and λ – the light wavelength in vacuum. Since by inclination of texture axis when spattering the thin -film ZnO piezotransducer, we obtain the equal amplitude excitation of both fast (V_f) and slow (V_s) share acoustic waves, then it is possible to get the regime in which the wave will be synchronized for either ordinary or extraordinary light by simple overtuning of the control frequency. For the chosen example of lithium niobate crystal the share wave velocities are: $V_s = 3.7$ km/s, $V_f = 4.2$ km/s, so the required control

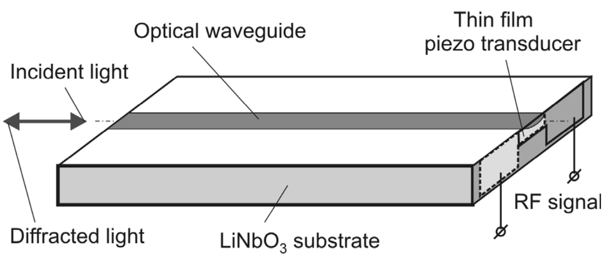

Fig. 7. Integrated collinear AO tunable mirror.

frequency must be $f_s = 10.700$ GHz and $f_f = 12.194$ GHz correspondingly. The experiments described in work [4] show the possibility of realization of lithium niobate based AO device at such high frequencies although big sound attenuation in this material restricts the spectral characteristics of such a device. Nevertheless this principle can be successfully used for other sufficient materials and frequency ranges.

3.4. Bragg cells based on resonant AO condition

The set of effective high frequency AO devices can be built based on the effect of resonant acoustooptical conditions [8], when the optical wavelength tends towards the band gap in semiconductor materials such as GaAs or InP. Calculations show that 8% diffraction efficiency can be reached in resonant conditions in InP crystal for the light wavelength in the region 900–910 nm, when the applied electrical power does not exceed 1 mW. Such attractive features make it possible to create a number of signal

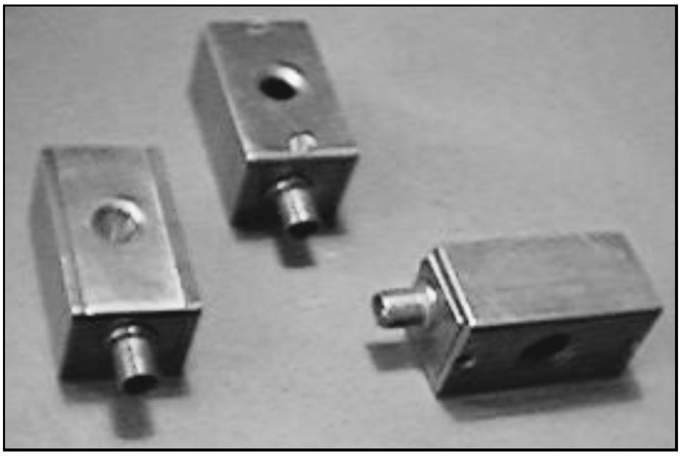

Fig. 8. The 2 GHz central frequency and 1.5 GHz bandwidth near infrared light deflectors based on resonant AO effect.

processing devices with unique parameters. Thus, for example, the AO switch for about 32×32 and more channels for optical fiber use can be easily designed for the wavelength of 1.3 μm which is much desired for telecommunication purposes. In Figure 8, AO deflectors based on AO resonant condition for near infrared light region, with central frequency of 2 GHz and 1.5 GHz bandwidth are shown.

3.5. AO holographic display for 3D moving image reconstruction

Application of high-frequency multielement array for excitation of complicated sound field offers the possibility of building an information display with bulk holographic image reconstruction.

The basic idea of such a kind of display consists in substitution of a classical static optical hologram by a dynamic optical hologram created by refraction index variation

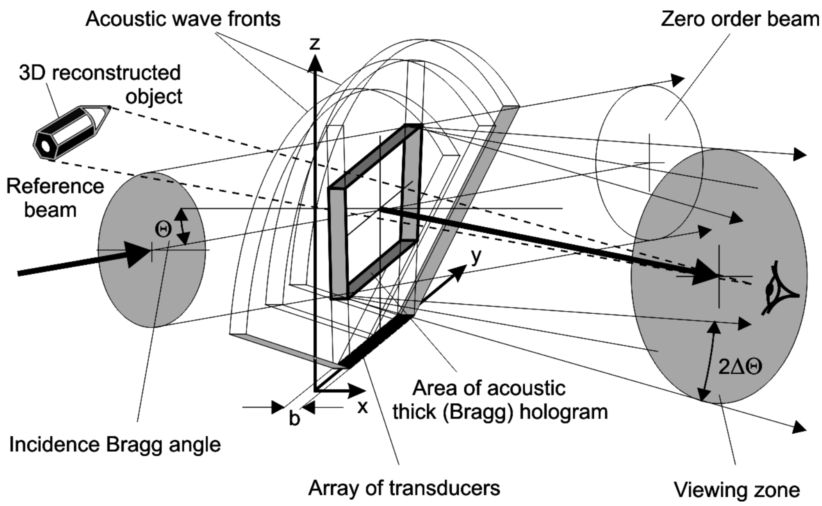

Fig. 9. Architecture of holographic display based on AO interaction.

stipulated by the action of complicated high frequency sound field [9]–[11]. It is assumed that the transmission functions of both static optical hologram and dynamic acoustically created optical hologram are equal at a certain instant of time. Figure 9 illustrates the architecture of such an information display.

This sound field is created by the set of unique thread-type transducers each of which excites a wide angle, wedge divergent sound beam. Electrical signals which are directed to the transducers come from the computer controlling driver. These signals are formed according to a special algorithm, which takes into account the sound attenuation, divergence of each beam, distortion of pixels and other peculiarities. Such an electronically created dynamic optical hologram is illuminated at a certain instant of time when the whole frame is formed. The sequence of electronically controlled continuously changed frames allows recreating bulk holographic moving image. Each unique transducer has a thread-kind shape that together with high frequency regime stipulates formation of a thick optical hologram similar to so-called Denisyuk hologram [12]. Such a hologram can be called the Bragg acoustically created hologram as it allows the Bragg diffraction of light on such a hologram. The Bragg regime allows to achieve the following goals: to concentrate the energy in one of the first order diffraction; to enhance the diffraction efficiency; to enlarge the space resolution; using the anisotropic regime of diffraction – in order to cut the useless zero order transmitted and scattered light. In spite of a number of problems which are encountered when building such systems, this approach seems prospective for large application areas.

3.6. Other applications

It is possible to continue the list of applications of acoustooptics at very high frequencies to include very well known ones: acoustooptical tunable filters for spectrum analysis, radio-pulse compression and radio-signal spectrum analysis for radar systems; but due to the limited space of this paper we just briefly mention some of them.

– When creating acoustical microscopes for frequencies above 1 GHz one can meet the problem of how to digitise the short time signal, which outputs from acoustical objective. The acoustooptical architecture of sound microscope offers some original solution.

– Acoustooptics can be successfully used to improve optical beam characteristics for two-dimensional spatial filtration [13].

– Application of AO cell in non-linear regime allows realising both the AO bistability and chaos model [14].

– AO devices based on the effect of optical heterodyning with feedback demonstrate the features of laser-like acoustooptical generator [15], [16].

– The diffraction light tomography can be realised on the basis AO effect [17].

– Wavelet AO filtration [18].

4. Conclusions

The great attractiveness of high frequency acoustooptics stemming from its advantages such as: big absolute frequency bandwidth; Bragg regime of diffraction, which allows optical energy to be saved in one diffraction order; short sound wavelength, which can be compared with optical one and others. The restriction on shifting to higher frequencies mainly concerns high sound attenuation in known materials suitable for acoustooptics. But in spite of that problem, taking into consideration the peculiarities of AO cells design, there are some ways of building the effective real time systems based on high frequency acoustooptics.

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