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Transmission characteristics of acousto-optic filter using sectioned transducer

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ABSTRACT

The paper examines operation of a tunable acousto-optic filter applying a sectioned piezoelectric transducer. The analysis was carried out for a tellurium dioxide cell having 1.4-cm long transducer divided into 7 identical sections connected in series. Each section generated acoustic waves with a time delay relatively to adjacent sections. The time delay caused electric and acoustic phase shifts as well as inclination of a resulting acoustic wave front in the crystal. We showed that the inclination of the acoustic front influenced on shape of the filter transmission function causing asymmetry of side lobes. Investigation of the filter was carried out at the driving acoustic frequencies 100–240 MHz. The measurement proved that the electric phase shifts between the adjacent sections increased with the frequency up to 30°. Ratio of intensities of the first two side lobes in the transmission function was varying with the frequency from 0.9 to 0.5. Based on the carried out analysis, we discussed a prototype device using the acoustic beam steering effect. The device applied two sets of transducer sections that simultaneously generated two acoustic wave fronts tilted with respect to each other.

1. Introduction

Tunable acousto-optic filters (AOTFs) and deflectors are extensively applied in optics, spectroscopy, optical communication, astronomy, laser technology, etc. [1–3]. The AOTFs are also used for image processing in the ultraviolet, visible and infrared range of optical spectrum [4–11]. In addition, the imaging wide angle AOTFs can execute filtering of spatial frequencies of laser radiation and form images in monochromatic light [12–14]. The devices combine simultaneous functions of spectral filtering, modulation and optical polarization control in real time [1–3,6]. The paper provides theoretical and experimental investigation of an AOTF and a deflector applying extended piezoelectric transducers divided into sections [1,2,15–22]. It is known that diffraction efficiency and spatial resolution in the acousto-optic devices increases with the growth of effective length of light and sound interaction. In is also evident that the effective length can be increased by application of extended, i.e. a few centimetres long, transducers.

In scientific literature, we found many papers devoted to investigation of the wide angle AOTFs operating with divergent and convergent optical beams [4–14]. Spectral bandwidth of filtering and optical transmission coefficient of the filters depend on dimensions of applied piezoelectric transducers. As mentioned, the spectral bandwidth becomes narrower and the transmission coefficient increases with the growth of the transducer length along light propagation direction. In addition, requirements on driving electric power become less strict in the case of longer transducers [1–3]. That is why, the transducers having relatively long dimensions along light propagation direction are actively applied in modern AOTFs. For example, the imaging paratellurite (TeO_2) filter designed for processing of images in the middle infrared region of spectrum has a transducer length $l = 3.2$ cm [7]. The imaging AOTFs based on KDP crystals transparent in the ultraviolet range of optical wavelengths, applied the transducers with the length $l = 3.0$ cm [4,5]. Since spatial resolution and optical throughput in the imaging AOTFs increase with linear optical apertures, it is necessary to increase not only lengths but also widths of transducer plates. In the AOTF based on TeO_2 crystal described in the Ref. [8], the width of a piezoelectric transducer was equal to 1.5 cm.

The increase in the length and width of a transducer inevitably results in extremely large square of the transducer plate. It is evident that the large dimensions of the transducers result in big magnitudes of their static electric capacitor and relatively low active resistance [1,2]. This drawback may be compensated by special design of acousto-optic cells. Usually the compensation is carried out by subdivision of the transducer plate into a number of sections and electrical connection of the sections in series. This

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commonly used method of transducer fabrication usually solves the problem of electric matching of a transducer with a driving RF generator [1–5]. On the other hand, a filter applying multiple transducers demonstrates operation parameters different from those in a filter designed on base of traditional single-plate transducers.

It was found that propagation of a driving electric signal from one section to an adjacent section in a multiple transducer is accompanied by a time delay and consequently by a phase shift $\Delta\varphi$ of a driving electric signal. The shift of the phase of the electric signal is automatically translated into a corresponding phase shift of acoustic waves generated by sections of a multiple transducer. It means that effect of acoustic beam steering may be expected in an AOTF. Therefore, the goal of the present investigation consists in analysis of phase delays and in a sectioned transducer. We also discuss influence of the phase shifts on diffracted light intensity. In particular, we examined dependence of the diffracted light intensity on frequency of the driving electric signal. As known, this dependence determines transmission function and spectral characteristics of the imaging AOTFs [1–3].

2. Electric signal phase delays between transducer sections

We examined a typical wide angle AOTF fabricated of a single tellurium dioxide crystal [1–4]. In the AOTF, a piezoelectric transducer was made of lithium niobate crystal. We used X-cut of lithium niobate crystal to generate slow shear acoustic waves in (1 1 0) plane of the material at the angle 10° relatively to the axis [1 1 0]. General scheme of the acousto-optic cell is shown in Fig. 2. The transducer consisted of $N = 7$ identical sections connected in series. The driving electric signal was applied to the driving electrode of the first section of the transducer, while one of the electrodes of the 7-th section crystal was electrically connected to the ground.

We registered that the electric phase of the driving signal in the filter was changing from one section to another. It caused time delays in the acoustic waves generated by the adjacent sections. That is why, the resulting acoustic wave front launched by the transducer in the crystal occurred tilted relatively to the bottom facet of the cell. Registration of the different from zero time delays between the adjacent sections indicated that the multiple transducer could electrically be represented by an electric delay line. It is known that the equivalent electric scheme of a piezoelectric transducer may be represented by a parallel connection of the static capacitor C_0 together with the oscillatory circuit having the capacitor C, the inductor L and the resistor R [2,3]. In the examined case of the multiple transducer, the electric parameters R, L, C and C_0 described a single section of the transducer. As for the adjacent sections of the transducer, they were connected in series by means of small metal stripes. These stripes are seen in Fig. 1. It is clear that the connecting elements possessed parasitic inductors L_i. Moreover, all sections of the multiple transducer were characterized by parasitic capacitors C_p evaluated with respect to the electric ground state.

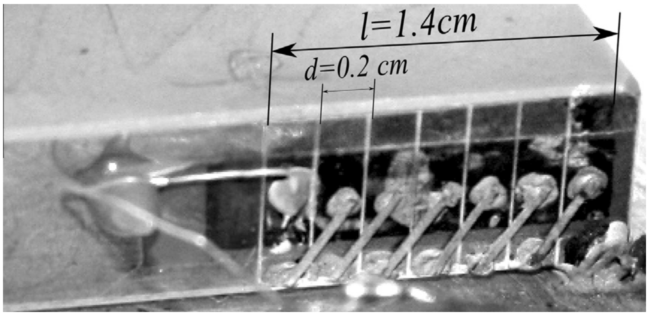

Fig. 1. View of AOTF based on TeO_2 crystal having extended piezoelectric transducer divided into 7 sections connected in series.

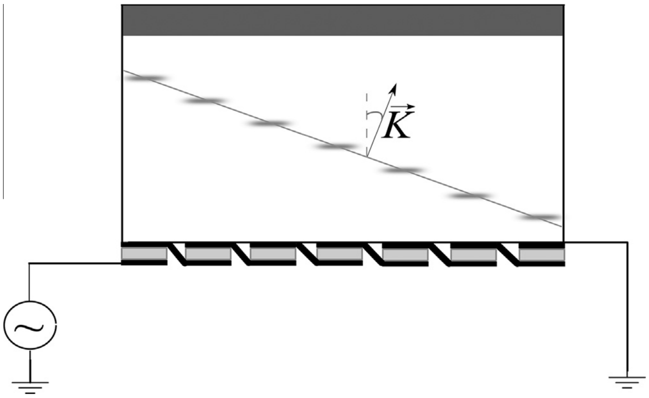

Fig. 2. Scheme of AOTF having piezoelectric transducer divided into 7 sections (period of the structure 0.2 cm, gap between sections 0.02 cm).

In order to investigate the phase shifts in the described electric delay line, first we measured frequency dependences of the total electric impedance $Z(f)$ in the examined filter and the return power loss RL(dB) in the electric line connecting the AOTF with a driving radio frequency generator [23]. In this way, we determined the interval of frequencies f corresponding to the optimal performance of the AOTF. Both characteristics were measured using Rohde & Schwarz Network Analyzer ZVL. The relation between the input electric power P_0 and the acoustic power P launched in the filter is described by the expression [23]:

$$P/P_0 = 1 - 10^{0.1RL(\mathrm{dB})}, \qquad (1)$$

where RL(dB) is the return loss of power measured in the wide range of electric frequencies f = 40–340 MHz. Data on the measured dependence of the ratio P/P_0 is shown in Fig. 3. As for Fig. 4, it shows Smith Chart illustrating the dependence of the electric impedance Z on the frequency f. According to Fig. 3, the optimal operation interval of the AOTF was limited to the frequencies f = 100–240 MHz, therefore all basic measurements and calculations were carried out in this frequency range.

As mentioned, the equivalent electric scheme of the examined multiple transducer was represented by the circuit shown in

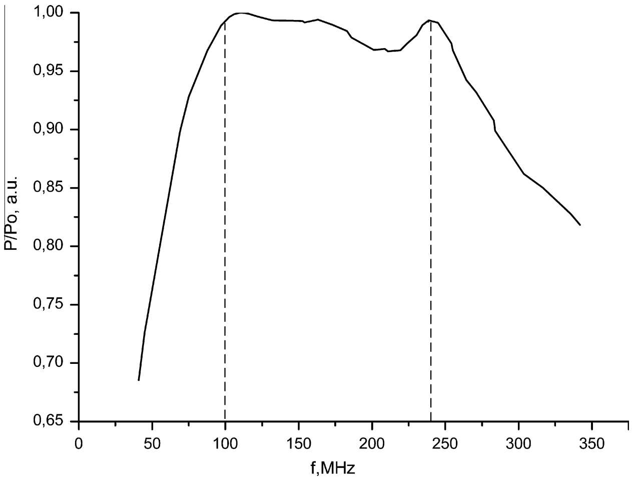

Fig. 3. Frequency dependence of relative acoustic power in the filter.