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Electronic tuning of acoustic resonances in acousto-optic mode lockers

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ABSTRACT

The effect of electronic tuning of acoustic resonances in an acousto-optic mode locker is studied theoretically and experimentally. The tuning is implemented by means of changing a matching inductance connected to the transducer in parallel. Experimental investigations are carried out with a mode locker made of a fused quartz with a lithium niobate transducer. Varying magnitude of the inductor from 0.025 to 0.25 mH has made it possible to retune the acoustic resonance frequency by 0.19 MHz, i.e. wider than the acoustic resonance half-width.

1. Introduction

At present, acousto-optic (AO) methods of light beam regulation find wide applications in many areas of science and technology. Numerous investigations have proved high efficiency of the AO regulation of amplitude, frequency, phase and polarization of optical waves [1–3]. Such AO devices, as modulators, deflectors and filters, are distinguished by a high speed of operation, low driving voltage, reliability and simplicity of design. These advantages have enabled their wide applications not only in laser physics but also in ecology, medicine, and military technology.

One important application of AO effect is locking of longitudinal laser modes by means of modulating the internal losses of a laser at a frequency equal to the frequency difference between adjacent modes. For this purpose, an AO modulator is used as a rule, which is placed into the laser cavity [4–12]. When a standing acoustic wave with a frequency f is excited in the modulator cell, the intensity of an optical beam passing through the cell changes with a frequency $2f$. The most strong mode locking effect takes place, when the frequency $2f$ becomes equal to the intermode frequency range $\Delta\nu = c/2L$, where c is the light velocity, L is the laser resonator length. The mode-locked laser generates a sequence of short optical pulses with repetition rate $c/2L$ and duration $\tau \approx 2L/cN$, where N is the number of locked modes.

An important requirement for implementation of the mode-locked laser is a good temperature stabilization of both the laser and especially the AO mode locker. If during the laser operation the temperature changes at least by several degrees, the AO modulator length and the acoustic velocity alter so much that the condition $\Delta\nu = 2f$ breaks down and the mode locking effect disappears.

Recently we have revealed in our experimental studies of AO mode lockers that the resonances of the modulator can be retuned by means of changing reactive elements of a matching circuit incorporated between the RF generator and the modulator transducer. This effect opens up the way to creating a feedback system for stabilization of acoustic resonance frequency. The given paper presents both theoretical analysis of the revealed effect and some preliminary experimental results.

2. Theoretical analysis

Fig. 1 illustrates the statement of the problem. Suppose that a piezoelectric plate has a thickness h and an AO modulator represents a Fabry–Perot resonator with a length l along the ultrasound propagation. Since the thickness h is much less than transversal dimensions of the piezoelectric plate, we can consider our electro-acoustic problem in one-dimensional approximation. In this case, the solution of the problem should be searched in the form of standing waves:

$$u_1 = M\ \exp[j(\Omega t - K_1 z)] + N\ \exp[j(\Omega t + K_1 z)] - \quad (1)$$

for the transducer and

$$u_2 = P\ \exp(-\alpha z)\exp[j(\Omega t - K_2 z)] + Q\ \exp(\alpha z)\exp[j(\Omega t + K_2 z)] - \quad (2)$$

for the AO medium. Here $K_1 = \Omega/V_1$ and $K_2 = \Omega/V_2$ are the propagation constants in the piezoelectric plate and AO medium

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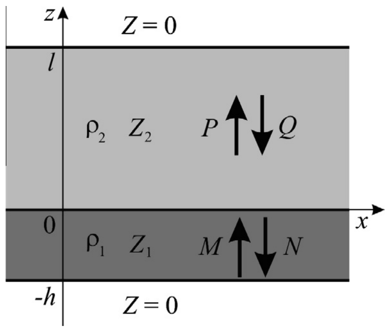

Fig. 1. Geometry of AO mode locker (statement of the problem).

respectively, V_1 and V_2 are the acoustic velocities. The coefficient α takes into consideration acoustic attenuation in the AO cell. Boundary conditions for acoustic stress T and displacement u have the following forms:

$$T_1(-h)=0,\quad T_1(0)=T_2(0),\quad T_2(l)=0,\quad u_1(0)=u_2(0). \tag{3}$$

Substituting (1) and (2) into wave equations and taking into account boundary conditions (3), we can derive the following expression for the acoustic admittance:

$$Y_a=\frac{j\Omega C_0 F\cos F}{F\cos F-k^2\sin F}\times\left\{1-\frac{k^2(1-\cos F)^2(E+1)}{\cos F(Z_a/F)(\beta+jF)(E-1)(F\cos F-k^2\sin F)+(E+1)\left[F\sin F-2k^2(1-\cos F)\right]}\right\}, \tag{4}$$

where $E=\exp[-2\gamma(\beta+jF)]$, $\gamma=V_1l/V_2h$, $\beta=\alpha V_2h/V_1$, $F=K_1h$ is the normalized frequency, C_0 is the static capacity of the transducer, k is the electromechanical coupling constant, $Z_a=\rho_2V_2/\rho_1V_1$ is the relative acoustic impedance, ρ_1 and ρ_2 are the densities of piezoelectric and AO media. A detailed derivation of Eq. (4) is very cumbersome; it will be presented in another paper.

The complex character of Eq. (4) makes it possible to present the transducer in the form of a resistor $R(\Omega)$ and a capacitor $C(\Omega)$ connected in parallel:

$$Y_a=\frac{1}{R(\Omega)}+j\Omega C(\Omega). \tag{5}$$

Commonly, the RF generator feeding the transducer is attached through a matching circuit Z_1-Z_2 as shown in Fig. 2. This circuit provides better power transmission from the generator to the transducer. Assuming that the transducer is energized from the generator with EMF E_0 and internal resistance R_i, one can find from Fig. 2 that the amplitude of the voltage applied to the transducer is

$$U_0=\frac{E_0}{(R_i+Z_1)\left(Y_a+Z_2^{-1}\right)+1}. \tag{6}$$

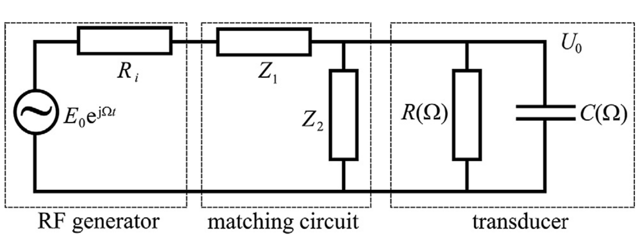

Fig. 2. Electrical transducer-generator matching circuit.

Hence we obtain the acoustic power as

$$P_a=\frac{|U_0|^2}{2R(\Omega)}. \tag{7}$$

The electric-to-acoustic conversion coefficient κ can be introduced as

$$\kappa=\frac{P_a}{P_{\text{match}}}=\frac{4R_i|U_0|^2}{E_0^2R(\Omega)}=\frac{4R_i}{R(\Omega)\left|(R_i+Z_1)\left(Y_a+Z_2^{-1}\right)+1\right|^2}, \tag{8}$$

where $P_{\text{match}}=E_0^2/8R_i$ is the power sent by the generator to the electrically matched load.

The standing acoustic wave in the AO cell can be written in the form

$$u_2(\tilde z,F)=P\{\exp[-\gamma(\beta+jF)\tilde z]+\exp[\gamma(\beta+jF)(\tilde z-2)]\}\exp(j\Omega t). \tag{9}$$

In this relationship, $\tilde z=z/l$ is the normalized coordinate and

$$P=U_0(1-\cos F)\frac{k}{V_1}\sqrt{\frac{\varepsilon}{\rho_1}}\left\{\frac{Z_a}{F}(\beta+jF)(E-1)(F\cos F-k^2\sin F)+\left(E+1\right)[F\sin F-2k^2(1-\cos F)]\right\}^{-1}, \tag{10}$$

ε is the relative dielectric permittivity of the transducer medium. The first term in (9) describes the wave traveling in the positive direction of the coordinate axis z, whereas the second component corresponds to the wave reflected from the free end of the AO cell.

3. Experimental results

Experimental investigations were executed with an AO cell fabricated of fused quartz. Longitudinal acoustic waves were excited with the help of a lithium niobate ($LiNbO_3$) transducer of 36° Y-cut [13]. The cell had antireflecting optical coatings for the wavelength 1.06 µm; it was intended for operation as a mode locker in a YAG:Nd laser at acoustic frequency close to 125 MHz. Nevertheless, the matching system provided effective excitation of ultrasound in the range from 111 to 158 MHz. Parameters of the AO modulator are presented in Table 1.

Characterization of the mode locker was carried out in regimes of both traveling and standing acoustic waves. In the former case

Table 1
Technical characteristics of AO mode locker.

AO medium	Fused quartz (SiO_2)
AO cell length	$l=5$ mm
Acoustic velocity in fused quartz	$V_2=5.96\cdot10^5$ cm/s
Acoustic impedance of fused quartz	$Z_2=13\cdot10^5$ g/cm² s
Transducer medium	Lithium niobate ($LiNbO_3$), 36° Y-cut
Transducer dimensions	3.2 × 3 mm²
Transducer thickness	27 µm
Static capacity	$C_0=125$ pF
Electromechanical coupling constant	$k=0.49$
Acoustic velocity in lithium niobate	$V_1=7.3\cdot10^5$ cm/s
Acoustic impedance of lithium niobate	$Z_1=34\cdot10^5$ g/cm² s
Relative acoustic impedance	$Z_a=0.38$