http://dx.doi.org/10.35596/1729-7648-2020-18-6-18-24

Original paper

UDC 535.5

AMPLITUDE MODULATION OF RADIATION BY COUPLED RESONATORS

ALEXEY I. KANOJKA

GNPO "Optics, Optoelectronics and Laser Technology" (Minsk, Republic of Belarus)

Submitted 3 March 2020

Abstract. In this paper, we describe a method that allows one to realize highly efficient amplitude modulation of radiation at the output of electro-optical laser switches with two coupled resonators, in which electro-optical elements are located both in two split arms and in every arm of a multipath interferometer with combined channels with a control voltage 2 times lower than in existing laser switches. Moreover, the electro-optical elements located in the two split arms of a multipath interferometer with combined channels, with one passage of the light flux through the electro-optical element, must make the opposite controlled changes in the phase difference of the interfering light beams. Therefore, for such electro-optical switches with two coupled resonators the value of the required electric power will be, respectively, 2 times less than that of the existing ones, which significantly expands their operating frequency range. In this case, a laser switch with electro-optical elements located in the two split arms of a multipath interferometer has an asymmetric dependence of the output radiation intensity on the change in the phase difference of the interfering light beams relative to the zero value of the light intensity. A laser switch with electro-optical elements located on all arms of a multipath interferometer with combined channels has a symmetric dependence of the output radiation intensity on the magnitude of the phase difference of the interfering light beams relative to the zero value of the light intensity. In addition, due to the coherent summation of the amplitudes of the interfering light waves, such laser electro-optical shutters also have amplification of radiation with a resonant wavelength.

Keywords: multipath interference, Fabry – Perot resonator, electro-optical effect, coherence.

Conflict of interests. multipath interference, Fabry – Perot resonator, electro-optical effect, coherence.

For citation. Kanojka A.I. Amplitude modulation of radiation by coupled resonators. Doklady BGUIR. 2020; 18(6): 18-24.

Foreword

Electro-optical shutters, that operate in the visible and near IR region of the spectrum, play a huge part in laser location and data transmission systems. Their function in the near IR region of the spectrum is characterized by a significantly larger control voltage as compared to the visible region. Thus, as a rule, such shutters exercise transverse application of the control electric field. In case of transverse electro-optical effect, intrinsic anisotropy of electro-optical crystals initiates dramatic tightening of the requirements to tolerable thermal instability. Therefore, the transverse electro-optical effect can be applied for modulation purposes only when the crystal is thermostated or temperature compensation circuits of natural birefringent effect are engaged [1, 2].

As the electro-optical medium for the working spectral range of interest, 3 m (lithium niobate – $LiNbO_3$) and mm2 (KTP – $KTiOPO_4$) crystals can be used. [1, 3, 4]. They are special for the almost constant electro-optical coefficients in a wide temperature range, which is of no small importance in field conditions. Lithium niobate crystals have a lower radiation strength and electro-optical coefficient than KTP crystals, which hampers their application for modulating the Q-factor of laser resonators. Thus, KTP crystals are of the greatest interest in terms of working spectral range, radiation strength, quantity and thermal stability of electro-optical coefficient.

Due to multiple interaction of light with the electro-optical medium, application of electro-optical phase modulation in multi-path interference devices for amplitude modulation of light allows a significant decrease in the control electrical voltage, which therefore increases the working frequency range of such modulators. [1, 5]. However, today's methods do not comprehensively consider the impact on the efficiency of amplitude modulation of multipath interference device specialties, which imposes substantial limits on the efficiency of such modulators. Present-day amplitude modulators based on multipath interference do not allow one to obtain highly efficient amplitude modulation of light radiation for the presence of big losses when irradiating the Fabry – Perot resonator [1, 6, 7].

This research sets an objective to consider the questions about a drop of control voltage of electro-optical laser switches based on multipath interference and an increase in their efficiency, which enables a dramatic augmentation of light modulation performance and expansion of their working frequency range.

Essence of the method

This method consists in implementing amplitude modulation of a plane polarized radiation based on electro-optical effect and multipath interference by loss-free irradiation of the system that encompassagees two coupled resonators with controllable Q-factor, which makes it possible to reach a significantly lower control electrical voltage and at the same time increase the efficiency of modulation.

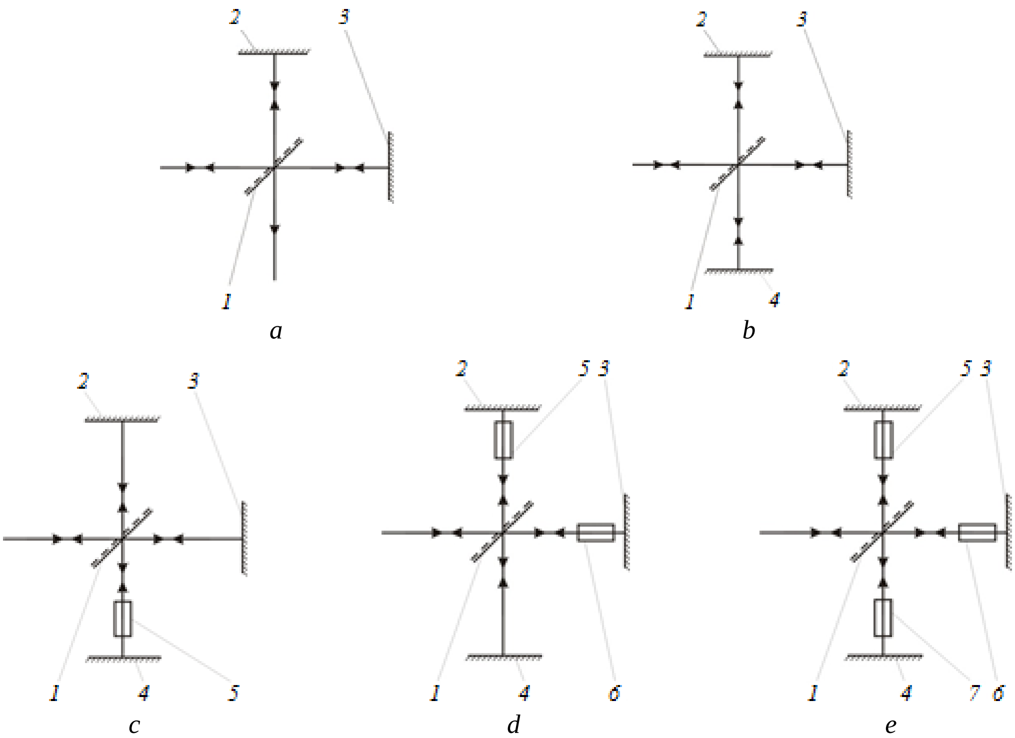


Fig. 1. Optical layouts of Michelson interferometer (*a*); a multipath interferometer with combined channels (*b*); a laser switch with an electro-optical element located in the common arm of multi-beam interferometer (*c*), in two split arms of multipath interferometer (*d*), in every arm of multipath interferometer (*e*)

The literature has numerous findings about the two-arm Michelson interferometer (Fig. 1, *a*) [1, 6, 7]. Should phase electro-optical elements with transverse application of the control field be introduced in both arms of the interferometer, a laser switch is formed with half the control voltage as compared to the present-day shutters. Its substantial drawback would consist in great light losses on the beam splitter. Should another reflector be introduced in the circuit of the two-arm Michelson interferometer, as shown in Fig. 1, *b*, we obtain the optical system of a two-channel multipath interferometer with combined channels where energy input is almost loss-free. The optical layout of a multipath interferometer with combined channels has one trait – input-output combination, which is what exactly needed for a laser switch. Based on such multipath interferometer, three possible optical layouts of a laser switch can be implemented (see Fig. 1).

Fig. 1, *c* depicts the optical layout of a laser switch with two coupled resonators where the electro-optical element is put in the common arm of the multi-beam interferometer. Fig. 1, *d* and Fig. 1, *e* demonstrate optical layouts of laser switches with two coupled resonators in which electro-optical elements are correspondingly placed in the two split arms and in every arm of the multi-beam interferometer, where *1* – beam splitter; *2*, *3*, *4* – reflectors; *5*, *6*, *7* – electro-optical elements. Electro-optical elements can represent electro-optical crystals, e. g. litium niobate $LiNbO_3$ or KTP with control electrodes deposited on their lateral faces.

Results and discussion

Consider the fundamental regularities in the function of such multipath interferometer with combined channels and of laser switches that are implementable on its base.

In initial condition, the input of a multipath interferometer under consideration is fed with a monochromatic plane-wavefront light beam with intensity I_0. Then it is divided by beam splitter *1* into two light beams with equal intensities, i. e., $I_0/2$, and thus their amplitudes will equal

$$E_{0i} = \sqrt{\frac{I_0}{2}}. \tag{1}$$

After being reflected on the first *2*nd and the second *3*rd reflectors, they repeatedly arrive to the beam splitter that takes one half of radiation out of the optical layout of the laser switch and directs the other half to the third reflector *4*th. The radiation from the third reflector goes to the beam splitter where it is divided into two light beams with equal intensities that travel to the first and the second reflectors, etc. Assume $\delta_1 = \delta_2 = \delta_3 = \delta$ – phase difference induced in interferometer's arms; $\Delta\delta$ – controllable variation in phase difference of interfering light beams in case of one passage through the electro-optical element; $T_1 = R_1 = K = 0.5$ – transmission and reflection coefficients of the beam splitter; $R_2 = R_3 = R_4 = R$ – reflection coefficients of the first, second and third reflectors, respectively; then the output of the interferometer would have a light beam with the amplitude of electromagnetic oscillations equal to the total amplitude of re-reflected waves.

Total amplitude of light wave at the output of a multipath interferometer with combined channels can be found from the expression below:

$$E_\Sigma = \frac{2E_{0i}K\sqrt{R}}{1-2e^{i2(\delta+\Delta\delta)}KR}. \tag{2}$$

Then the expression for total light intensity at the output of a multipath interferometer with combined channels is:

$$I_{out} = E_\Sigma E_\Sigma^* = \frac{2I_0K^2R}{1+(2KR)^2-4KR\cos 2(\delta+\Delta\delta)}. \tag{3}$$

The provisions reported were compared to the experiment results. The optical layout of the experiment setup is shown in Fig. 2. Composition: laser *1* (LG-207A) that generates constant 1 mW radiation with wavelength $\lambda = 0.6328$ μm; polarizing isolation unit *2* consisting of polarizing splitter *3*, polarization twister *4* and reflector *5*, *6*, *9*, *10* are, respectively, the first, second and third reflectors of coupled resonators; *7* – light radiation power meter (OPHIR meter with NOVA-II display, 3A-SH measurement sensor, Power Accuracy: ±3 %, Power Noise Level: 2μW); *8* – beam splitter. Examinations of multipath interferometer with combined channels have proven good correlation of estimated and experimental performance.

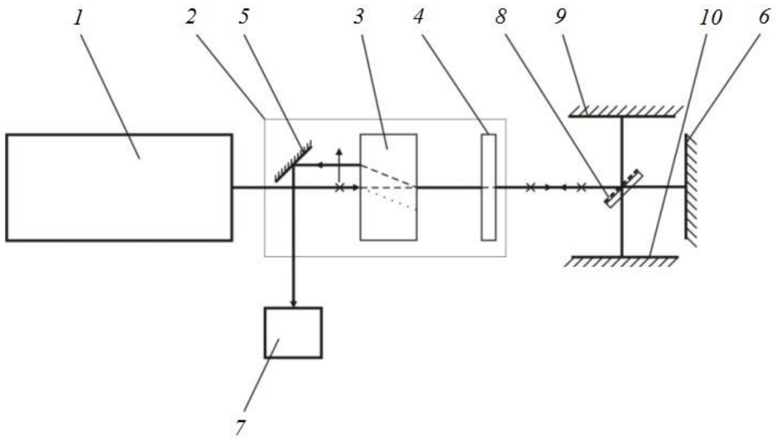


Fig. 2. Optical layout of a laboratory setup for studying coupled resonators

Consider a laser switch with two coupled resonators (see the optical layout in Fig. 1, *c*) where amplitude modulation is done through variation in the phase difference of interfering light beams in the common arm of a multipath interferometer. This can be achieved by either introducing one electro-optical element to the linear arm or attaching reflector *4* with a piezoelectric drive which ensures enough precision in adjusting optical distance of the common arm, and therefore the difference of phases δ induced therein. combined channels and of laser switches that are implementable on its base.

In initial condition, the input of the laser switch under consideration is fed with a monochromatic plane-wavefront light beam with intensity I_0. Then the first beam splitter divides it into two light beams with equal intensities, i. e. $I_0/2$, and therefore the amplitudes of their electromagnetic oscillations will be determined by expression (1). After being reflected on the first and the second reflectors, they repeatedly arrive to the beam splitter that takes one half of radiation out of the optical layout of the laser switch and directs the other half to the third reflector. The radiation from the third reflector goes again to the beam splitter to be divided into two light beams with equal intensities that travel to the first and the second reflectors, etc.

Assume that T_5 is the light transmission of the electro-optical element. Then, the output of such laser switch would have a light beam with the amplitude of electromagnetic oscillations equal to the total amplitude of re-reflected waves which can be found from the expression below:

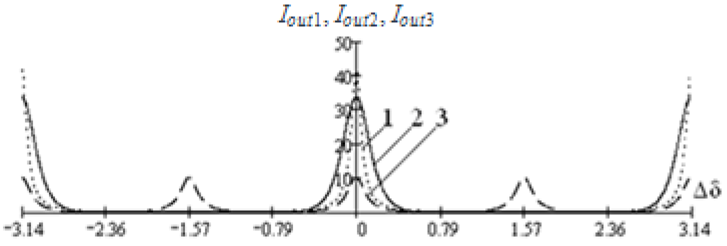
$$E_{\Sigma 1} = \frac{2E_{0i}K\sqrt{R}}{1-2e^{i2(\delta+\Delta\delta)}KRT_5}. \tag{4}$$

Then the expression for the total light intensity at the output of the laser switch (see the optical layout in Fig. 1, *c*) is:

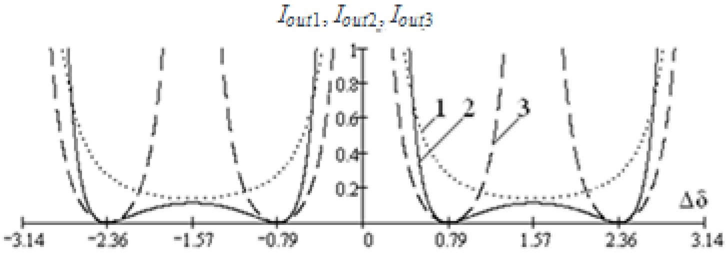
$$I_{out1} = E_{\Sigma 1}E^*_{\Sigma 1} = \frac{2I_0K^2R}{1+\left(2KRT_5\right)^2-4KRT_5\cos 2\left(\delta+\Delta\delta\right)}. \tag{5}$$

Fig. 3 (curve 1) demonstrates the dependence of the total light intensity at the output of the laser switch on the variation of Δδ phase differences at the following parametric values: $I_0 = 1$; K=0.5; R = 0,99; T_5=0,9. This dependence clarifies that such laser switch does not have sufficient SNR.

Spectral distribution of the light intensity at the output of such switch is given in Fig. 4, *a*. The mechanism of amplitude modulation of such laser switch consists in a shift of spectral maximum of radiation intensity in case of corresponding variation in Δδ phase difference. Directions of the shift are illustrated with arrows.

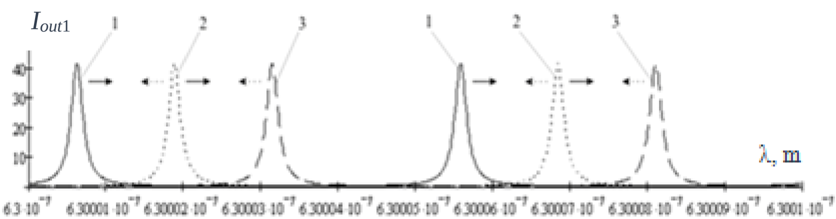


a



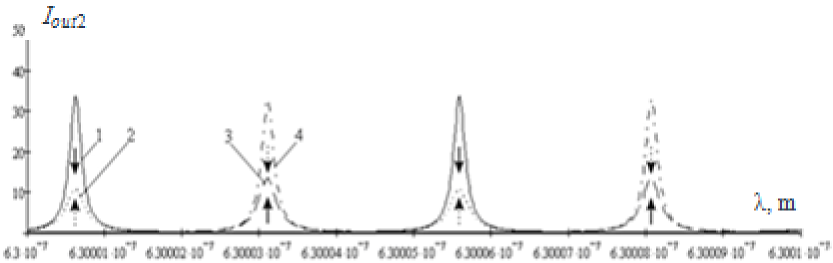
b

Fig. 3. Dependences of the intensity of the output radiation in the laser switch I_{out1}, I_{out2}, I_{out3} on the magnitude of the variation in the phase difference of the interfering light beams $\Delta\delta$: *a* – general view; *b* – for values of light intensity not exceeding 1



1; 2; 3 – spectral intensity distribution respectively at $\Delta\delta = 0$; $\pi/4$; $\pi/2$

a



1; 2; 3; 4 – spectral intensity distribution respectively at $\Delta\delta = 0$; $\pi/16$; $7\pi/16$; $\pi/2$

→ ◄··· – the directions of the shift of the spectral maximum respectively when increasing and decreasing the induced phase difference $\Delta\delta$

b

Fig. 4. Spectral distributions of light intensity at the switch output with coupled resonators I_{out1}, I_{out2} when the induced $\Delta\delta$ phase difference variations, respectively, with an electro-optical element located in the common arm (*a*); with electro-optical elements located in the split arms of a multipath interferometer (*b*)

The dependence from Fig. 3 (curve 1) demonstrates that the downside of such optical system of a laser switch consists in the impossibility to obtain low control voltage in the first place and low SNR in the second place.

Therefore, the point of interest is to consider the optical system of a laser switch (see Fig. 1, *d*). Here electro-optical elements lie in the two split arms of a multipath interferometer and initiate opposite controllable variations in the phase difference of interfering light beams in case of one passage through the electro-optical element.

Assume $T_5 = T_6$. Then the total amplitude of light wave at the output of the laser switch where electro-optical elements lie in the two split arms of a multipath interferometer can be found through the expression below:

$$E_{\Sigma 2} = \frac{2E_{0i}KT_5\sqrt{R}\cos 2\Delta\delta}{1-2e^{i2\delta}KRT_5\cos 2\Delta\delta}. \qquad (6)$$

Then the expression for total light intensity at the output of such laser switch is:

$$I_{out2} = E_{\Sigma 2}E^*_{\Sigma 2} = \frac{2I_0K^2T_5^2R\cos^2 2\Delta\delta}{1+\left(2KRT_5\cos 2\Delta\delta\right)^2 - 4KRT_5\cos 2\delta\cos 2\Delta\delta}; \qquad (7)$$

Fig. 3 (curve 2) gives the dependence of total light intensity at the output of the laser switch on the variation in $\Delta\delta$ phase difference. This dependence makes it clear that such laser switch has its first maximum at $\Delta\delta = \pi/4 = 0.79$, which is achieved by applying control voltage $U_{\lambda/8}$.

Fig. 4, *b* demonstrates spectral distribution of light intensity at the output of such switch. The amplitude modulation mechanism of such laser switch consists in shifting the amplitude of the spectral maximum of radiation intensity to zero with further increase at a different wavelength to the maximum in case of varying phase difference $\Delta\delta = \pi/4$. Directions of the shift are illustrated with arrows.

The optical system of the laser switch under consideration benefits for it ensures high modulation efficiency at the control voltage of about $U_{\lambda/8}$, which is two times less than the existent electro-optical shutters have.

The laser switch considered has the dependence of output radiation intensity on the variation value of phase difference of interfering light beams $\Delta\delta$ which is asymmetrical relative to zero light intensity (Fig. 3, curve 2).

Thus, the point of interest is to consider the laser switch with electro-optical elements lying in every arm of a multipath interferometer with its optical layout depicted in Fig. 1, *e*. Here electro-optical elements that lie in the two split arms of a multipath interferometer should initiate opposite controllable variations in the phase difference of interfering light beams in case of one passage through the electro-optical element. The variation in phase difference of interfering light beams in the common arm of a multipath interferometer can match that in one split arm.

Assume $T_5 = T_6 = T_7$. The total amplitude of light wave at the output of such laser switch can be found from the expression below:

$$E_{\Sigma 3} = \frac{2E_{0i}KT_5\sqrt{R}\cos 2\Delta\delta}{1-2e^{i2(\delta+\Delta\delta)}KRT_5^2\cos 2\Delta\delta}. \qquad (8)$$

Them the expression for total light intensity at the output of the laser switch is:

$$I_{out3} = E_{\Sigma 3}E^*_{\Sigma 3} = \frac{2I_0K^2T_5^2R\cos^2 2\Delta\delta}{1+\left(2KRT_5^2\cos 2\Delta\delta\right)^2 - 4KRT_5^2\cos 2\left(\delta+\Delta\delta\right)\cdot\cos 2\Delta\delta}. \qquad (9)$$

Fig. 3 (curve 3) shows the dependence of total light intensity at the output of the laser switch on phase difference variation $\Delta\delta$. This dependence makes it clear that such laser switch has the first minimum at $\Delta\delta = \pi/4 = 0{,}79$, which is achieved by applying control voltage $U_{\lambda/8}$.

The laser switch considered has symmetrical dependence of output radiation intensity on the variation value of the phase difference of interfering light beams $\Delta\delta$ relative to zero light intensity (Fig. 3, curve 3). As in the previous case, the amplitude modulation mechanism of such laser switch consists in shifting the amplitude of the spectral maximum of radiation intensity to zero with further increase at a different wavelength to the maximum in case of varying phase difference $\Delta\delta = \pi/4$.

The optical system of the laser switch under consideration benefits for it ensures high modulation efficiency at the control voltage of about $U_{\lambda/8}$, which is two times less than the existent electro-optical shutters have. The laser switch considered has symmetrical dependence of output radiation intensity on the variation value of phase difference of interfering light beams $\Delta\delta$ which is asymmetrical relative to zero light intensity (Fig. 3, curve 3).

Conclusion

Therefore, the research completed has demonstrated that one can reach minimum control voltage and maximum efficiency of the amplitude modulation of radiation in electro-optical laser switches with two coupled resonators where electro-optical elements lie both in the two split arms and in every arm of a multipath interferometer with combined channels. Moreover, electro-optical elements in the two split arms of a multipath interferometer with combined channels must initiate opposite controllable variations in the phase difference of interfering light beams in case of one passage through the electro-optical element. The variation in phase difference of interfering light beams in the common arm of a multipath interferometer can match that in one of the split arms. For such laser switches the control voltage will be $U_{\lambda/8}$, which is two times less than the present-day laser switches have, which significantly expands its working frequency range. At the same time, the laser switch with electro-optical elements in the two split arms of a multipath interferometer possesses asymmetrical dependence of output radiation intensity on the variation value of the phase difference of interfering light beams relative to zero light intensity. The laser switch with electro-optical elements in every arm of a multipath interferometer possesses symmetrical dependence of output radiation intensity on the variation value of the phase difference of interfering light beams relative to zero light intensity. Besides, coherent summation of the amplitudes of interfering light waves makes the laser switch capable of enhancing radiation with a resonant wavelength.

References

1. Mustel E.R., Parygin V.N. [*Light modulation and scanning techniques*]. Moscow: Nauka; 1970. (in Russ.)
2. Adrianowa I.I., Zaslawskaja W.R. [Phased electro-optic modulator of non-parsed radiation]. *Optiko-mechanicheskaja promyschlennost = Optical-mechanical industry.* 1978;6:24-26. (in Russ.)
3. Iona F., Schirane D. [*Ferroelectric crystals*]. Moscow: Mir; 1965. (in Russ.)
4. Nai Dzh. [*Physical properties of crystals*]. Moscow: Mir; 1967. (in Russ.)
5. Yariw A., Yuch P. [*Optical waves in crystals*]. Moscow: Mir; 1987. (in Russ.)
6. Nagibina I.M. [*Light interference and diffraction*]. Leningrad: Maschinostroenie; 1985. (in Russ.)
7. Born M., Wolf E. [*Optics fundamentals*]. Moscow: Nauka; 1973. (in Russ.)

Information about the author

Kanojka A.I., PhD, Associate Professor, Senior Researcher of the photoelectronics laboratory of SSPA “Optics, optoelectronics and laser technology”.

Address for correspondence

220090, Republic of Belarus,
Minsk, Logoyskiy tract, 22,
SSPA “Optics, optoelectronics and laser technology”
tel. +375-44-746-63-72;
e-mail: kon54@yandex.by
Kanojka Alexey Ivanovich