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Electro-Optical Modulators for Radio Photonics Systems

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Abstract. The article considers the principles of operation of electro-optical Mach–Zehnder modulators. Methods for transferring the received microwave radiation of the tested radar to the optical carrier frequency are presented. Connection schemes and modulation formats are given.

Keywords: electro-optic modulators Mach-Zehnder, the controller operating point, the driver of the modulating signal, wiring diagram, modulation formats.

Introduction

An amplitude electro-optical modulator according to the Mach–Zehnder interferometer scheme is the main version of an external modulator in analog and digital fiber-optic communication lines (FOCL) [1, 2]. The advantages of this device include: high modulation frequency; compactness; reliability. Modulators are also used in fiber optic sensors, measuring equipment, radio signal transmission over optical fiber, and radio photonics [3].

Fiber-optic communication lines have significant advantages for aviation: low weight and volume, immunity to electromagnetic pickups, complete explosion safety, wide bandwidth. Replacing copper conductors with fiber optics allows not only to reduce the weight and increase the reliability of aircraft, but also to reduce the overall cost of the information transmission system on the aircraft.

The disadvantages of electro-optical Mach–Zehnder modulators include their high cost, as well as their susceptibility to various drift phenomena.

Mach–Zehnder radiation intensity modulators are manufactured by iXBlue Photonics (France), Lumentum Holdings Inc. (USA), Optilab (USA), Covega (USA), EOSpase (USA), Thorlabs (USA), Oclaro (USA), Laser 2000 (UK), JENOPTIK (Germany), Sumitomo Osaka Cement (Japan), Fujitsu (Japan)), OKI Electroniks Components (Japan), Lucent Technologies (China), SWT (China), ECI (Israel), NPK Optolink (Russia). The list is incomplete.

Electro-optical Mach–Zehnder (MMZ) modulators are intensity modulators of the interferometric type. A schematic representation of the modulator chip from iXBlue Photonics (France) is shown in fig. 1.

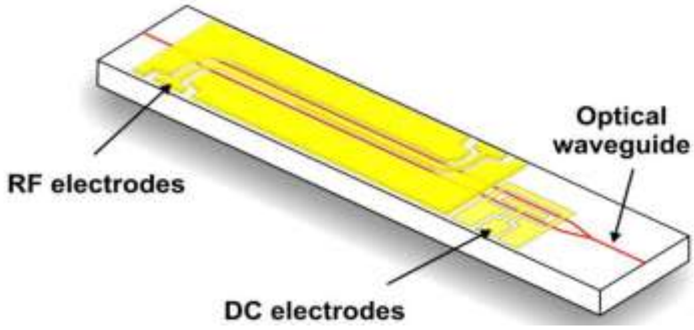

Fig. 1. Schematic representation of the modulator chip from iXBlue Photonics1 [4]: RF electrodes – modulation electrodes; DC electrodes - bias electrodes

Physics of electro-optical modulators

An electro-optical modulator (EOM) is a device that, using a control voltage, can control the value of the energy, phase, and polarization of an optical signal [5]. Such modulators are based on crystals, which, under the influence of an electric field, exhibit an electro-optical effect, that is, they are an electro-optical medium.

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The refractive index of an electrooptical medium is a function of *n(E)* of the applied electric field *E* [6]. This function changes only slightly with *E*, so it can be expanded in a Taylor series:

$$n(E) = n + \frac{1}{2}a_1 E + \frac{1}{2}a_2 E^2 + ... \quad (1)$$

where are the expansion coefficients $n = n(0)$, $a_1 = (d\,n/dE)_{|E=0}$ and $a_2 = (d\,n^2/d\,E^2)_{|E=0}$.

Expression (1) is usually written in terms of the so-called electro-optical coefficients $r = -2\,a_1/n^3$ and $\xi = -a_2/n^3$, then it takes the form:

$$n(E) = n - \frac{1}{2}rn^3 E - \frac{1}{2}\xi n^3 E^2 + ... \quad (2)$$

The terms of the third and higher orders in this series, as a rule, are several orders of magnitude smaller than the refractive index, because of which they can be neglected.

The change in refractive index is usually very small. However, its effect on light propagating in a medium whose length is much longer than the wavelength of light can be significant [6].

Electro-optical effects are subdivided into the Pockels effect and the Kerr effect.

Electro-optical Pockels effect

The Pockels effect is a linear electro-optical effect, as a result of which birefringence in an optical medium changes or is produced and the refractive index of the medium changes due to the action of an electric field [6, 7]. The Pockels effect is manifested in non-centrosymmetric materials. For example, lithium niobate ($LiNbO_3$), lithium tantalate ($LiTaO_3$), indium phosphide (InP) are Pockels cells, that is, materials exhibiting the Pockels effect.

In the Pockels cells, the third term of formula (2) is negligible compared to the second, that is, the dependence of the refractive index on the electric field has the form illustrated in Figure 2 [6]:

$$n(E) \approx n - \frac{1}{2}rn^3 E \quad (3)$$

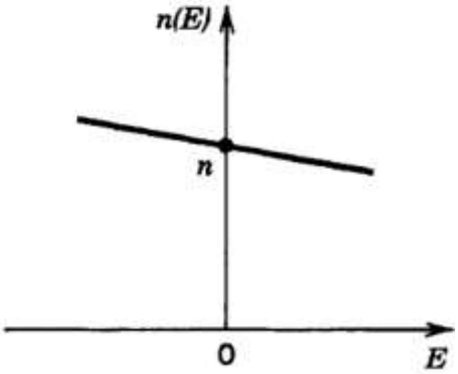

Fig. 2. Dependence of the refractive index on the electric field in Pockels cells [6]

The coefficient r in formula (3) is called the Pockels coefficient or the linear electro-optical coefficient. Typical values of the coefficient lie in the range $10^{-12} - 10^{-10}$ m/V [6].

The properties of the Pockels cell depend on the orientation of the crystal structure of the cut plate. The cut of a crystal is denoted using Cartesian coordinates. For example, if the Z-axis coincides with the normal to the slice plane, then the slice is called a Z-slice. Figure 3 shows a schematic representation of such a cut.

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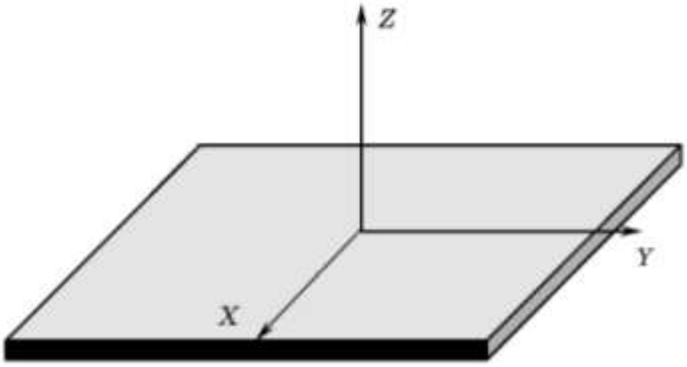

Fig. 3. Schematic representation of the Z-cut plate [8]

For example, in a lithium niobate crystal, the main difference between the cuts is that the X-cut has birefringence, while the Z-cut does not. Different cuts of a crystal also have different electrooptical, acoustooptical, and other coefficients [9].

Based on the Pockels effect, devices for electrical control of coherent optical radiation have been developed. The low inertia makes it possible to modulate light up to frequencies of ~10^13 Hz, as well as change the quality factor of lasers and obtain powerful light pulses of nanosecond duration.

Electro-optical Kerr effect

The Kerr effect is a nonlinear electro-optical effect, which consists in changing the value of the refractive index of an optical material in proportion to the square of the applied electric field strength [10]. If the material exhibiting the Kerr effect is centrosymmetric, then *n(E)* is also a symmetric function, since it must be invariant to a change in the electric field, as shown in Figure 4 [6].

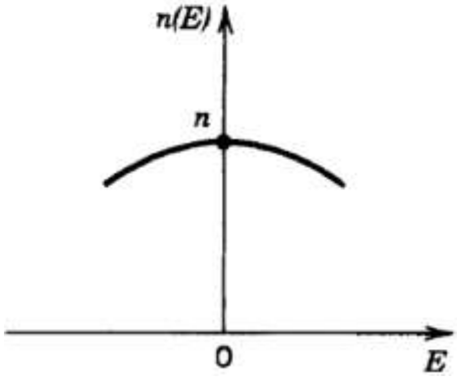

Fig. 4. Dependence of the refractive index on the electric field in the Kerr effect [6]

The dependence of the refractive index on the electric field strength in the Kerr effect is described by formula (4) [6]:

$$n(E) = n - \frac{1}{2}\xi n^3 E^2 \qquad (4)$$

Materials exhibiting the Kerr effect are called Kerr cells and include not only crystals, but also gases and liquids. The parameter ξ is called the Kerr coefficient or the quadratic electro-optical coefficient. Typical values of the coefficient in crystals are 10^{-18}–10^{-14} m^2/V^2, and in liquids 10^{-22}–10^{-19} m^2/V^2 [6].

Amplitude modulator

An electro-optical amplitude modulator can be made in the form of a polarization modulator placed between two polarizers – a polarizer at the input of the crystal and an analyzer at the output of the crystal [5].

The amplitude modulator based on the MZM also contains two beam splitters and two mirrors. The phase shift in the shoulder is provided by using a phase EOM. A schematic representation of such a modulator is shown in Figure 5.

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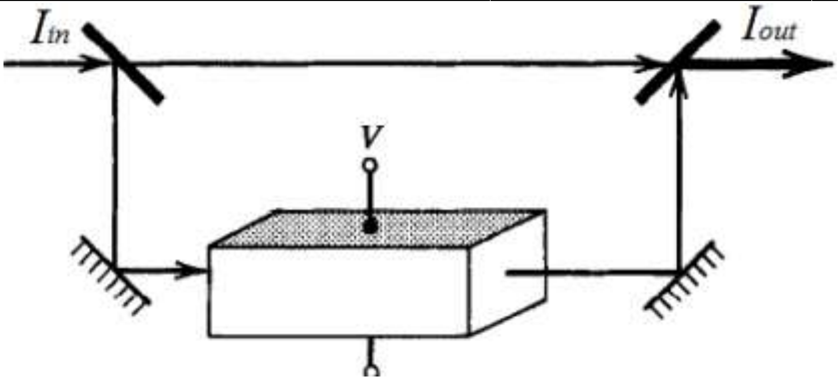

Fig. 5. Mach-Zehnder modulator (MMC): I_{in}- input radiation intensity, I_{out} - output intensity [6]

Amplitude modulators based on the MMC are also made in the form of integrated optical devices using waveguides.

Conclusions

Mach–Zehnder modulators are a key element of high-speed transmission equipment for FOCL. The 100 Gb/s DQPSK format requires only 50 Gb/s optical and electrical components.

Great prospects for the use of Mach–Zehnder modulators in radio photonics systems (MWP - Microwave Photonics microwave photonics). Broadband radio-photonic analog paths with external modulation are based on modulators; ultra-wideband radio-photonic frequency converters (mixers); radiophotonic highly stable microwave self-oscillators of harmonic signals; ultrawideband radiophotonic analog-to-digital converters.

The research and production company Optolink (Zelenograd, Russia) produces precision fiber-optic gyroscopes based on its own special modulators.

Initially, electro-optical Mach–Zehnder modulators based on lithium niobate were developed for telecommunication systems. Extensive experience in their manufacture and application has been accumulated. The long-term aging tests carried out by the H. Nagata group for four years (35000 h) demonstrated the exceptional reliability of Mach–Zehnder modulators based on lithium niobate.

The modulators operate at different wavelengths and are highly reliable. Their areas of application are expanding.

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