Magnetooptical Switches

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A short review on optical switches with emphasis on magnetooptical methods is presented. A novel magnetooptical switch of latching type with an yttrium orthoferrite optical rotator is described. The crystal remains in a given magnetic state for unlimited duration without energy supply. The response time is about 30 ns, the aperture of the optical rotator is 350 μm.

Key words: Optical switching, latching, Faraday effect, orthoferrite

1. Introduction

Optical switches are in great demand for a large variety of photonic applications, optical communication being only the most prominent one. Electrooptic, electroabsorptive and acoustooptical switches are, due to their unsurpassed speed, widely used and great research efforts are focused on microelectromechanical systems (MEMS) because of their array-character. Recently, electroholographic switches have been introduced that combine switching with filtering behavior. New ideas use stimulated Raman scattering in an all-fiber switching scheme1) or chiral change of molecules2) with transition times in the nanosecond range. All of these technologies have specific merits and shortcomings. Magnetooptic switches have, — despite several distinctive advantages such as high power handling capability — played only a minor role up to date because of the large magnetic fields required for switching.

Recently, however, we have introduced a new class of magnetooptic switches that rely on orthoferrites, transparent magnets. These materials combine large Faraday rotation with ferromagnetic bistability; this means that they require driving power only during switching. These switches combine high power capability, low transmission losses and latching behavior with a switching speed in the nanosecond range. Electrooptic or acoustooptical switches may be even faster, but require sophisticated driving electronics and/or are limited to low power applications. In this article, we present a new development of orthoferrite-based magnetooptic switches which relies on the recently discovered magnetic aftereffect in this class of materials. This effect allows to combine different domain structures, thus adding multi-stability to the features of orthoferrite switches.

2. State of the art

In the following we present a short review about optical switches with emphasis on magneto-optical set-ups.

2.1 Mechanical designs

A classical example of a mechanically controlled switch involves an optical fiber that is attached to a rotating wheel and can be aligned with a number of optical fibers attached to a fixed wheel. Modern designs are using moving mirrors in MEMS5)-7) — also using permanent magnets for latching operation9) and integrated waveguides10) — which can be easily arranged in N × N matrices11) for an optical switch fabric12) and networks.13) Other schemes are using fluids within a capillary, controlled by means of an asymmetric bubble chamber to provide latching optical switching14)-16) or thermocapillary.17)

Mechanical switches and switches on the base of liquid crystals have the advantage of stable states in which they remain without energy consumption. In addition, they are insensitive to wavelength and polarization of light. A drawback of these switches is a low operation speed.

2.2 Magneto-optical designs

Magneto-optics offers compromise solutions. As compared with mechanical devices it does not require any moving parts, resulting in much less sensitivity to mechanical vibrations or shock, and much higher operation speeds at the expense of dependent performance. As compared with high speed electro-optical and acousto-optical devices it offers stable states, and thus high reliability without permanent energy consumption.

In magnetooptical switches light is manipulated by means of a Faraday rotation of the input polarization plane: depending on the sense of polarization rotation a polarization beam splitter mounted behind the optical rotator directs the light in one of two output channels18),19) In previous versions of magnetooptical switches (first works performed at Fujitsu Company) the latching type of operation was based on the magnetic hysteresis of the yoke material.

A principal scheme of a polarization-independent switch is based on a bistable Faraday rotator. The input ports are 1 and 2 and the output ports are 3 and 4. For one magnetization direction of the rotator light from input port 1 reaches the output port 3 and light from the port 2 reaches the output port 4. Switching of the magnetization direction
causes switching of the emergent light beams between the output ports. The magneto-optical materials used in these works represented compositions of iron garnets. These materials themselves do not possess a rectangular hysteresis loop and, consequently, they cannot remain magnetized at high remanence in the absence of the external magnetic fields. Latching type of operation was obtained by placing the MO material in the field of an electromagnet with a semi-hard magnetic material core. By passing an electric current pulse through the windings the core was magnetically saturated. After the pulse the core and the MO material remained magnetized, resulting in a rotation of the polarization plane of the transmitted light. A change of the polarity of the electric current pulse caused change in the sense of rotation of the polarization plane. Both states were stable without any energy consumption. However high inductance of the electromagnet strongly restricted the operation speed: response time of commercially available switches is several hundred microseconds.

3. Latching switch based on orthoferrites

We have developed a new magnetooptical switch based on orthoferrite.\textsuperscript{20-23} Orthoferrites have a formula $\text{RFeO}_3$, where R is a rare earth ion or yttrium. They are transparent in the visible and in the near infrared regions of spectrum. Orthoferrites are canted antiferromagnets: magnetization vectors of ion sublattices are not strictly antiparallel but rather form a small canting angle of about $0.5^\circ$.\textsuperscript{24} The canting results in a small resultant magnetization which is responsible for gyrotropic properties of these crystals. For all orthoferrites except the samarium one, the resultant magnetization at room temperatures lies along the crystallographic c-axis. Despite low value of the resultant magnetization specific Faraday rotation of orthoferrites in the range of their transparency is rather high. This is due to the contribution of the antiferromagnetism vector in the non-diagonal component of the dielectric tensor.\textsuperscript{27} The highest values of magneto-optical figure of merit (ratio of specific Faraday rotation to absorption) are possessed by yttrium orthoferrite. At the wavelength of 1550 nm specific Faraday rotation of YFeO$_3$ equals 240 deg/cm whereas it’s absorption coefficient can be as small as 0.05 cm$^{-1}$.

Orthoferrites are optically biaxial crystals, their birefringence in the direction of the "easy" axis is about $4 \times 10^{-2}$ and this sufficiently influences polarization properties of the transmitted light: linearly polarized light becomes elliptically polarized and angle of rotation of the large axis of the polarization ellipse cannot exceed several degrees. Large, proportional to the thickness angles of the polarization rotation are obtained when light propagates along optical axis of the crystal. In yttrium orthoferrite optical axes lie in the crystallographic $bc$ plane and for the wavelengths of 1300–1500 nm form angles of 46 degrees with the axis of weak ferromagnetism, crystallographic c-axis. Low resultant magnetization of YFeO$_3$ $(M_r < 10 \text{ mT})$ in combination with a strong uniaxial magnetic anisotropy $(K_u = 15 \text{ kJ/m}^3)$ result in very large, up to several hundred micrometer wide domains in the crystal. In addition, canted magnetization of the samples cut perpendicularly to the optical axis, provides rectilinear walls of the stripe domains thus enhancing their attractiveness for applications. Furthermore, the walls can be moved at velocities up to 20 km/s without changing of Faraday rotation in domains.

The principle of operation of the new orthoferrite switch is based on the recently found rapid demagnetization (RD) phenomenon.\textsuperscript{25} This phenomenon consists in a rapid division of a crystal into domains with a given dependence of spatial magnetization distribution on the previously acting magnetic field. If the value of an external driving magnetic field does not exceed the value required to magnetize the orthoferrite crystal to a monodomain state, then after removal of the field the crystal spontaneously divides into domains again. Whereas usually aftereffects are studied in the presence of holding fields close to coercivity value and the demagnetization process lasts minutes or even hours, RD in orthoferrites observed in the absence of a holding field develops on a microsecond scale.

3.1 Experimental set-up

The experimental setup of the switch was mounted on the base of the commercially available fiberoptic polarization splitter and included a semiconductor cw laser $\lambda = 1300$ nm connected to the input port, a first birefringent crystal B1, polarization rotator, a $\lambda/2$ plate, and a second birefringent crystal B2.

The polarization rotators represented cuboids from yttrium orthoferrite single crystals. Front surfaces of the samples formed an angle of 46$^\circ$ with the crystallographic c axis. The thickness of the samples was 1.1 mm, corresponding to 45 degrees of Faraday rotation. The coercivity of the sample is about 40 kA/m. The cross section of the samples had a height of 1.2 mm and a width of 2 mm. The samples were embraced by 1.5 mm long coils consisting of 10 windings. The birefringent elements B1 and B2 represented commercially available calcite prisms OFR-PBB-10 which shifted the P-polarized light beam at 1 mm with respect to the unaffected S-polarized light beam.

3.2 Domain structure

Figure 1 shows photographs of the domain structure in the orthoferrite crystal. To obtain the images a broad, plane polarized laser beam was transmitted through the rotator, analyzer whose main plane formed angle of 45$^\circ$ with the main plane of the polarizer, an objective and was collected by an infrared viewer. Three domains are seen. In Fig. 1a the middle domain is bright, i.e. the analyzer mounted behind the crystal transmits light propagating through this domain. In a stable equilibrium state, the sum of the volumes of the peripheral domains has to be equal to the volume of the central one. The requirement of volume matching is particularly stringent for thick crystals. According to this, in our sample the widths of the peripheral domains have to be 300 $\mu$m each (a quarter of the height). In order to increase the widths of peripheral domains needed for practical applications,
one can introduce metastable states with unequal widths. This can be performed by means of DW-pinning through scratches on the surfaces of the crystal. In Fig. 1 one can see two lines of scratches separated by 510 μm (they were applied to the front and rear faces of the crystal). Due to the pinning, the peripheral domains became larger, i.e. 350 μm wide, on expense of the middle domain.

By application of a magnetic field of appropriate polarity the sample becomes magnetized in the direction of the middle domain and after removal of the field the sample demagnetizes into domains with inverted magnetization directions. Thus by transmitting light through a certain part of the sample consequently occupied by domains of alternative magnetization the direction of rotation of the polarization plane of the light beam can be switched. For the middle domain the change of the magnetization direction (and of the sense of polarization rotation) occur only after the end of the driving magnetic field pulse whereas for the upper and for the lower domains the changes occur soon after switching on of the pulse.

### 3.3 Results

In our experiments we directed both light beams emergent from the first birefringent crystal B1 through the lower domain. The laser spot diameter is about 300 μm. Fast axis of the λ/2 plate (mounted behind the rotator) formed an angle of 22.5° with the vertical. Photograph of the light beams emergent from the second birefringent crystal B2 are shown in Fig. 2. Two light beams are seen. Insets illustrate polarization and directions of the light beams. Figure 2a shows the case when rotation of polarization plane occurs in the clockwise direction. Then at the entry of the second birefringent crystal B2 polarizations of the light beams are the same as of the beams emergent from the B1 crystal. The S polarized beam propagates further in the same direction whereas the P-polarized beam is deflected for the second time. After application of the driving magnetic field pulse the rotation of the polarization plane changes sign and polarizations of the light beams at the entrance of the second birefringent crystal are opposite to those for Fig. 1a. The crystal shifts the P-polarized light beam towards the S-polarized one and the both beams combine in one at the exit from the crystal. The resultant beam is focused on the exit fiber coupler thus providing a shutter or a 1 x 1 switch mode of operation (see Fig. 2b).

Figure 3 shows oscillograms of the switch. The lower curves show the absolute value of the current in the coil. The amplitude of the current equals 2 A, corresponding to a field of 16 kA/m. Upper curves show signals of the photodetector connected to the exit fiber. Figure 3a demonstrates “opening” of the switch, Fig. 3b shows the closing of the switch. Opening of the switch occurs in 30 ns, closing occurs in 65 ns. In these time intervals the expanding domain covers both light beams. Switching times depend on the parameters of the current pulse: they decrease with growth of amplitude and with shortening of its rise time.

Replacement of the second birefringent crystal B2 by the prism transforms the described element into a 1 x 2 switch. Replacement of the first birefringent crystal B1 by the prism as well, transform the element into the 2 x 2 switch.

### 4. Conclusions and Summary

A fast magneto-optical switch of latching type is developed. Response times of the switch are equal to several tens of nanoseconds, by four orders shorter than for commercially available magneto-optical switches. Principle of operation of the switch is based on the recently found rapid demagnetization. According to this phenomenon under certain conditions magnetized orthoferrite crystal spontaneously, within several microseconds demagnetizes into a set of domains with a known magnetization distribution. Using of this phenomenon provides substantial reduction of the driving magnetic fields and improvement of its stability.
Fig. 2: Schemes and photographs of the light beams emergent from the second birefringent crystal B2

To provide opportunity of switching of light beams with arbitrary polarization direction, in magnetooptical switches the incident light beam is decomposed into two beams with orthogonal polarization directions. In our switch both light beams are transmitted through the part of the rotator occupied by a single domain. Sign of magnetization direction of the domain coincides with a sign of the projection of the driving magnetic field on the "easy" axis direction. For one polarity of the driving magnetic field pulse the two separated beams at the exit of the switch are combined into one again and enter the output fiber. For the other polarity the beams remain separated and cannot enter the fiber. The switch is of $1 \times 1$ type. Replacement of polarization separating elements by respective prisms transforms it into the $2 \times 2$ switch.

The insertion loss of the switch is about 2 dB. It is determined by coupling of the optical fibers and by absorption losses in the crystal, which are 1.2 dB. At $\lambda = 1.55 \, \mu\text{m}$ the absorption of yttrium orthoferrite is substantially weaker and the losses in the crystal can as low as 0.1 dB.

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