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Optically Addressed Spatial Light Modulators

Pockels Readout Optical Modulator - PROM

Introduction

Pockels Readout Optical Modulator (PROM) is a typical optically addressed spatial light modulator (OASLM) with electro-optic (EO) photorefractive (PR) crystal used simulataneously as electro-optic and photoconductive mediums. PROM modulator is historically the first spatial light modulator (SLM) employing photorefractive crystals for EO modulation and photoconductivity. Classifications of SLM and their output parameters and structure are depicted in Figure 1, especially for two types of OASLM. The operation function of OASLM is to convert intensity distribution by the incident light or radiation beam into an output coherent image, or into a highly bright incoherent image. The applications of PROM type OASLM devices are in the following fields: from coherent dynamic optical processing and up to optically assisted detection of X-rays. The first PROM model based on epi ZnS, ZnSe films grown on GaAs crystal substrates was developed and manufactured at Itek corporation. Today PROM devices and modulator optical systems are based on active single sillenite type crystals: $Bi_{12}SiO_{20}$ (BSO), $Bi_{12}GeO_{20}$ (BGO) and semi-insulating SI-GaAs, which demonstrate the best parameters for output reading at visible and near IR spectral range. These sillenites are photorefractive crystals with a high gain and fast response.

Principle operating

The basic principle of OASLM PROM type modulators is the following. A photosensitive layer detects the writing beam intensity distribution and induces the electron charge distribution inside the crystal. Optical properties of the crystal occur to modify as a function of photo-induced electron charges or photo voltage. The applied electric bias forces to drift the mobile carriers to the crystal / dielectric interface until the electric field in the crystal was cancelled. The photo-induced space charge in the bulk crystal modulates the birefringence through the electro-optic longitudinal Pockels effect. The readout can be realized using a coherent light beam either in transmission or in reflection mode. The image contrast is modified by reapplying the bias on the modulator while reading the stored image. If the modulation is small, the contrast can by enhanced by substraction of constant voltage. An ability to modify the image contrast in real time is rather well useful for coherent optical processing applications.

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Fig 1 **SLM classifications**

<table>
<tr><td colspan="6">SLM</td></tr>
<tr><td colspan="5">OASLM</td><td>EASLM</td></tr>
<tr><td colspan="2">LC OASLM (LCLV, OALV)</td><td colspan="2">EO OASLM (PROM, PRIZ)</td><td>Hybrid OASLM</td><td rowspan="3">Digital Micromirror Device, etc</td></tr>
<tr><td>EO medium:</td><td>LC film layer</td><td>EO medium:</td><td rowspan="2">single PR crystal:
BSO, BGO, SI-GaAs</td><td rowspan="2">BSO/SI-GaAs,
BGO/SI-GaAs</td></tr>
<tr><td>PC medium:</td><td>PC crystal BSO,BGO
or
PC film layer</td><td>PC medium:</td></tr>
</table>

Output parameters and structure classification

Optical structure:	Transmission mode Reflection mode
Output modulation:	Phase / Polarization Amplitude / Intensity

Abbreviation:

SLM	spatial light modulator
OASLM	optically addressed SLM
LCLV	liquid crystal light valve
OALV	optically addressed light valve
EASLM	electrically addressed SLM
LC	liquid crystal
EO	electro-optic
LC OASLM	spatial light modulator with LC EO medium
EO OASLM	SLM with crystal EO medium
PROM	Pockels readout optical modulator
PC	photoconductive, photoconductivity
PR crystal	photorefractive crystal
BSO, BGO	$Bi_{12}SiO_{20}$, $Bi_{12}GeO_{20}$ single crystals
SI – GaAs	semi-insulating GaAs crystal

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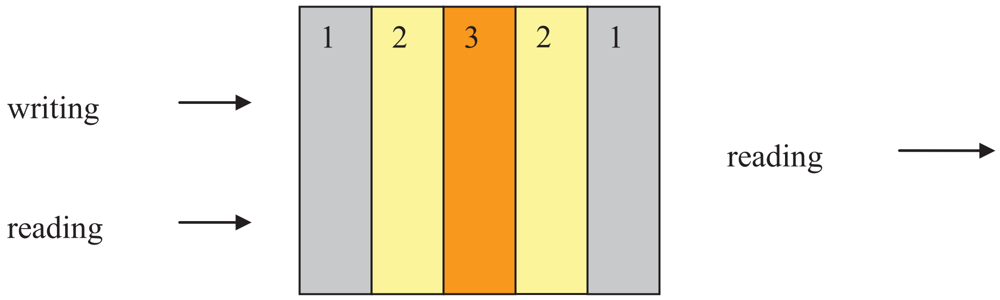
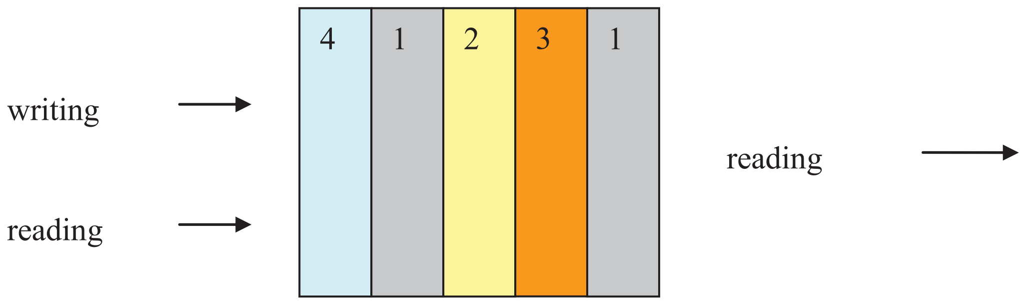
Construction and manufacture

Electro-optic PROM (and also PRIZ-type modulator developed at Ioffe Inst.) are devices with thin (0.1-1.0 mm) oriented crystalline plate of PR crystal placed between two transparent electrodes and one or two insulator layers. Figure 2 presents several types of PROM devices with different constructions. The M-D-C-D-M optical structure with two dielectric layers or with one dielectric layer for G-M-D-C-M structure is shown Fig. 2 (a), (b). When PROM operates in reflection mode, the dichroic layer reflects the readout light and transmits the write-down light passing through the crystal. Such M-D-MR-C-D-M structure is shown in Fig. 2.



(a)



(b)

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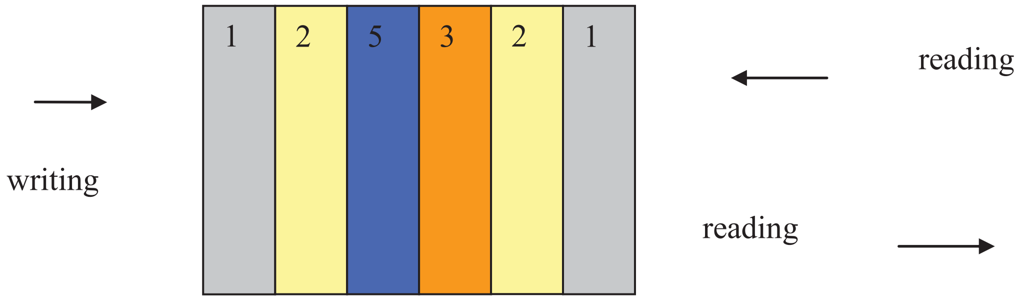

(c)

Figure 2. Schematic optical structure of PROM SLM.

(a): **M-D-C-D-M** structure, transmission mode
(b): **G-M-D-C-M** structure, transmission mode
(c): **M-D-MR-C-D-M** structure, reflection mode

Abbreviations: M - transparent electrode, D - transparent dielectric, C - photorefractive crystal, G - glass substrate, MR - dielectric dichroic mirror.

Transparent electrodes are made of ITO (Indium Tin Oxide) films or semi-transparent Pt metal layers. Dielectric layers are made of parylene or optical glue. Dielectric dichroic mirror is deposited on input frontside of the crystal; glass substrate is implemented with ITO electrode. Photorefractive crystal is the main component in the EO device and its optical and electro-optical properties determine input-output performance of PROM modulator. PR crystal can be selected in today market to get the required input-output PROM characteristics, for example variable wavelengths of the input writing light or X-ray beam, as well as variable wavelengths of readout light. PROM device can be design for visible spectral range with reading-out in the IR range. A new type PROM modulator can be developed, manufactured and supplied for customized applications for selected spectral ranges and incident radiation powers. The laboratory tests of main PR crystal parameters may be carried out by the assembler company using techniques of two wave mixing (TWM). This experimental method can be applied to estimate input-output characteristics of designed PROM modulator and EO systems. Below the properties of PR crystals are described briefly and possible selected constructions of PROM devices are noted.

Semiconductor PR crystals for PROM devices

Table 1 gathers semiconductor and optical properties of four well developed PR crystals. All these crystals are offered by the company for development of customized PROM modulators on request (spectral ranges, different writing scenes, and intensity of light or ray beams.

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Table 1 Optical, electro-optical and holographic parameters of photorefractive crystals.

Crystal	Point Group	* Operating wavelengths, μm	Dielectric constant ε_0	Electro-optic coefficient, pm/V	Holographic sensitivity, S, cm^2/J	Max Gain factor, cm^{-1}
BSO, undoped	23, cubic	0.4 – 0.6 blue-green	56	5 633 nm	500 at 514 nm	~ 10
BGO, undoped	23, cubic	0.4 – 0.6 blue-green	40	3.5 633 nm	400 at 514 nm	~ 8
SI - GaAs, semi-insulating	43m, cubic	0.8 – 1.8 near IR	12	1.2 at 1 μm	10^4 (10000) at 1.06 μm	6 – 7

* Operating wavelengths is the spectral range with maximum PR crystal photosensitivity and is used at ONE writing/reading wavelength for dynamic holography. This is employed mainly for PR crystal holography parameters, not for PROM devices. One should take into account the photosensitivity of crystals (for example the UV range is important for BSO, BGO crystals). But for such type writing all PR crystals strongly absorb nearby the front surface. At the same time, X-rays are absorbing in the bulk of crystals, for example, X-rays writing-down in BSO or BGO crystals.

X-ray image detection

PROM is optical imaging device, typically used with green-blue writing light. It designed on BSO, BGO single crystals, where the gamma-photon energy can be directly converted into electron-hole pairs. The X-ray absorption in the crystal bulk results in generation of charge carriers. After exposure the induced electric field at every point of the bulk is an exponential function of the absorbed X-ray energy in depth. The spatial variation contains a picture of the integrated X-ray flux. This picture is read out from PROM using polarized reading light that does not change photoconductivity and does not result in redistribution of charges in the crystal. The steady state optical phase distribution is read out by the transmitted polarized light through an analyzer to modulate the signal intensity and finally to record spatially varying X-ray exposed optical image.

In PROM-BSO (BGO) devices the X-rays with energy lower than about 8 keV do not usually produce large dynamic range X-ray images because of small penetration depth of low-energy x-ray photons (less 0.01 mm). Meanwhile, X-rays with energy of 20 keV to 160 keV (and expecting larger values of energy) can be absorbed in depth of 0.01 to 1.0 mm for BSO crystals.

Semiconductor semi-insulating electro-optical crystals can be efficiently applied for detection of X-rays, gamma-rays and other radiations. Semi-insulating doped single crystals as SI-GaAs, InP are displaying PR and photoconductive (PC) properties in IR range, and writing/reading ability with IR beams as well. (If we are going to write rays with energy > visible photons, reading range for semiconductor PR crystals to be in IR range of light wavelength with small photosensitivity for given crystal)

Hybrid SLM devices

As we considered before, in classic PROM one crystal is used simultaneously as electro-optic and photoconductive mediums. Composition of pair photorefractive electro-optic crystal plates mounted in one active crystal chip of PROM will be able to vary characteristics of SLM. Combinations of two crystals of PROM active crystal chip can be selected in dependence on requirements for reading optical system and writing rays. Linear EO crystal parameters are presented in Table 2 below for comparison and development of Pockels SLM devices including PROM.

Table 2. Linear electro-optical constants

Crystal	Point Group	Wavelength,λ μm	EO, r, pm/V	Refractive Index, n	n^3r, pm/V	Dielectric Constant
BSO	23	0.63	5	2.55	83	56
BGO	23	0.63	3.5	2.54	57	40
GaAs	43m	1.0	1.2	3.6	56	12

Conclusions

PROM-BGO (BSO) - type devices based on sillenite crystals are able efficiently to read UV, X - ray photons with simple red laser line writing/detection optical system.