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# Double phase conjugate mirror in CdTe:Ge

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**Abstract**

The coherent oscillation in double phase conjugate mirror (DPCM) geometry at 1.064 μm with ac or dc electric field applied to CdTe:Ge sample is reported. The threshold of oscillations and the conversion efficiency are studied at different electric field, total light intensity and intensity ratio of the pump beams. The conversion efficiency up to 50% is reached with rather poor fidelity which can be improved by means of a cylindrical telescope. A new architecture of all optical interconnect is proposed. An auxiliary illumination is used to control the coupling strength of the sample, switching it either below or above the threshold of oscillation. A prototype of optical switch is built that can connect one emitter/receiver to two other emitters/receivers. A switching time less than 5 ms is achieved at the intensities of the recording and erasing beams less than 100 mW/cm$^2$. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The double phase conjugate mirror (DPCM) is particularly interesting for bi-directional reconfigurable optical links [1]. However, the operation of DPCM requires large coupling strength ($\Gamma\ell > 4$) of the photorefractive crystals [2]. The gain factor of CdTe, being the largest among all infrared sensitive semiconductors, is, nevertheless, still much smaller as compared to that of wide-bandgap ferroelectrics. The photorefractive response can be improved by the external electric field. Two techniques are used now: in the first one a moving grating is recorded in the crystal with the applied dc field [3]; in the second approach the ac field is applied when stationary grating is recorded [4]. Both these techniques have been tested with the available CdTe:Ge samples and DPCM is obtained in the presence of ac or dc field. The threshold of oscillations and the conversion efficiency are studied for different electric field amplitude, total light intensity and intensity ratio of the pump beams. The influence of the erasing light on oscillation is studied and on/off switching is achieved. A new architecture of all optical interconnect is proposed. Two samples ensuring the oscillation in a wide range of experimental conditions are selected and prototype of 2 × 1 all optical interconnect is built up. The performance of this one-line interconnect is optimized both for high quality connection and for absence of the cross talks. The operation of the 2 × 1 interconnect for communication is demonstrated.

## 2. DPCM in CdTe:Ge

According to the theory [2] to achieve the oscillations the threshold coupling strength should

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be $\Gamma\ell \geqslant 4$. The largest coupling strength measured in two-beam coupling experiments with the applied field about 8 kV/cm was only slightly larger than this value. The oscillation was achieved, nevertheless, in all selected samples, most probably because the real small-signal gain factor is larger than that evaluated with rather strong signal wave. However the necessary conditions for successful operation are drastically different for samples with different conductivities. If the modulation frequency about 1 kHz is sufficient for reaching a good conversion efficiency in case of ac recording in R1 and R3 samples at least one order of magnitude higher frequency is needed for samples N90 and N91 because of their smaller resistivity. That is why dc technique is used for DPCM with N90 and N91 crystals while ac field is applied to R1 and R3 samples. In Fig. 1 the phase conjugate reflectivity $R_{\mathrm{PC}}$ is shown for samples R3 and N90 by filled and open squares, respectively, measured as a function of the applied field (a) and of the total pump intensity (b). $R_{\mathrm{PC}}$ is calculated as the intensity ratio of the diffracted beam and contra-directional pump beam. The absorption and Fresnel losses are not taken into account, i.e., the intensity of the pump beam is measured behind the crystal. When changing the amplitude of the external field we control the coupling strength of the sample. The threshold behavior of the oscillation is obvious, with the threshold field of about 2 kV/cm (dc) and 3 kV/cm (ac) for the samples N90 and R3, respectively. This relatively low threshold confirms that the maximum gain factor is underestimated in two-beam coupling experiments. In low intensity range the coupling strength depends also on the light intensity. That is why the oscillation occurs when certain threshold intensity is reached. This intensity is relatively low (3–4 mW/cm$^2$) for the studied CdTe samples. The intensity dependences of the phase conjugate reflectivity show the smooth increase until the saturation for sample 90 (open squares) and pronounced optimum intensity for the sample R3 (filled squares). The complicated intensity dependence of the phase conjugate reflectivity measured with R3 sample results from similar dependence of the two-beam coupling gain factor.

## 3. All optical interconnect

In this section we describe the new architecture of all optical interconnect and build up its prototype using DPCM in CdTe:Ge as a basic element. The schematic representation of $N \times M$-channel all optical interconnect with $N \times M$ optical switches controlled by $N + M$ auxiliary light beams is shown in Fig. 2(a) for $N = M = 3$. The signals $I_1, \ldots, I_6$ are carried by the laser beams. The switches are DPCM in photorefractive crystals. When two laser beams are coming to the switch a 3D phase grating is developing inside the crystals and two relevant channels become automatically coupled. This coupling can be controlled with the auxiliary (coherent or incoherent) light wave that can adjust the crystal coupling strength

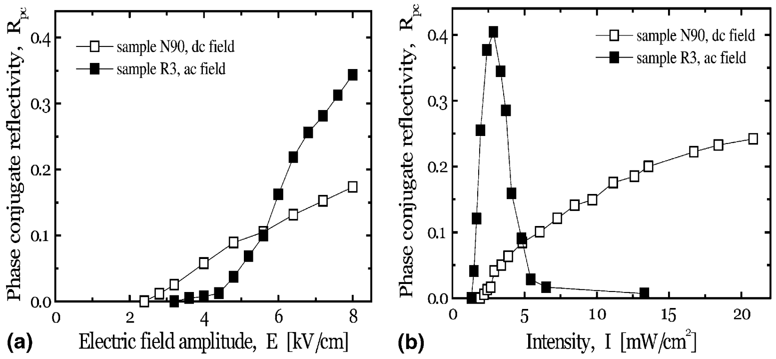

Fig. 1. Phase conjugate reflectivity of DPCM with CdTe:Ge versus applied field (a) and versus total pump intensity (b).

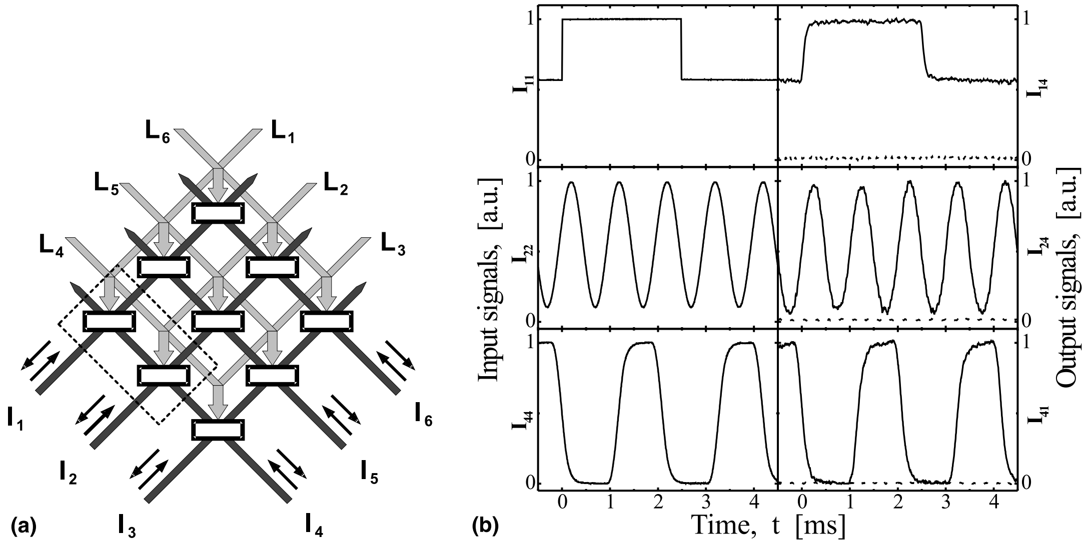

Fig. 2. (a) Schematic representation of 3 × 3 all optical interconnect; (b) temporal variation of the input and output signals (solid lines), dashed lines represent the output signal for the switched-off connection.

$\Gamma\ell$ below or above the threshold of oscillation. The auxiliary illumination increases the crystal conductivity and therefore reduces the space charge filed and $\Gamma\ell$. The reconfiguration of actual connections is performed by switching on or off the erasing beams $L_1, \ldots, L_6$. If, e.g., we intend to connect the channels $I_1$ and $I_5$ all erasing beams should be switched on except $L_1$ and $L_5$.

One-line optical interconnect is built up with $N = 1$ and $M = 2$ using the samples N90 and N91. The choice of the samples is determined by wider range of input intensities and by faster response as compared to R1 and R3 crystals. They are also relatively transparent, total transmission through the sample with uncoated input/output faces is nearly 30%. CdTe samples serve as two switches shown within dashed line window in Fig. 2(a), connecting the signals $I_1$, $I_2$ and $I_4$. The beam from the diode-pumped $\mathrm{Nd}^{3+}$ : YAG laser emitting at 1.064 μm is used as a carrier. It is splitted into three input beams ($I_1, I_2$ and $I_4$). Every input beam passes through the amplitude modulator. An acoustooptic modulator is used in the beam 1, an electrooptic modulator is used in channel 2 and a mechanical chopper is used in the third channel $I_4$. The cw radiation of the 1.3 μm $\mathrm{Nd}^{3+}$ : YAG laser is used to form the control beams. This choice has no special justification; any coherent or incoherent light source with the spectrum fitting to photoconductivity bands of CdTe and sufficiently high intensity can be used too. The initial idea to use 1.3 μm radiation was related to possible sensitizing of CdTe:Ge for 1.06 μm recording [5]. Such a sensitizing was really achieved with sample R3 but it occurs only for carefully adjusted intensity of 1.3 μm radiation that depends on overall 1.06 μm radiation intensity on the sample. The necessity to adjust the intensity of the control beam to any variation of 1.06 μm radiation intensity that may happen makes this sensitizing process not practical for the design of interconnect. That is why we finally use more powerful 1.3 μm light ($80\ \mathrm{mW/cm^2}$) to increase strongly the photoconductivity of the sample and to erase partially in such a way a grating recorded by 1.06 μm radiation. In front of amplitude modulators the beam splitters are placed sending a part of the reflected back radiation to the photodetectors. The angle between the interacting waves in air is $180° - 0.7°$ (the grating spacing is about 40 μm). With the external electric field of 8 kV/cm this spacing is optimized for getting the largest conversion efficiency; in "open" position the 3% of the input radiation is diffracted from the transmission grating.

Fig. 2(b) presents by solid lines the temporal variation of the input signals measured just after respective optical modulator ($I_{22}$, e.g., stands for the signal of the emitter in channel 2, i.e., emitted in 2 and measured at 2) and signals that are coming from the other channels ($I_{24}$, e.g., stands for the signal emitted in 2 and measured at 4). One-to-one correspondence of the emitted and received signals is obvious. Dashed lines correspond to the switched-off connection. The system is checked also for possible "echo" effect: $I_{24}$ is measured with no modulation in channel 4 but with modulated signal 2. No temporal variations are observed in $I_{24}$ for sufficiently high modulation frequency 2 (when the grating amplitude cannot follow the high frequency intensity modulation).

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