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Photorefractive gain enhancement in InP:Fe using band-edge resonance and temperature stabilization

James E. Millerd, Steffen D. Koehler, and Elsa M. Garmire
National Center for Integrated Photonic Technology and Center for Laser Studies, University of Southern California, University Park, Los Angeles, California 90089-1112

Afshin Partovi and Alastair M. Glass
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Marvin B. Klein
Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, California 90265

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We report photorefractive two beam coupling gain coefficients as high as $\Gamma = 19\ \text{cm}^{-1}$ and net gains of Γ-$\alpha = 14\ \text{cm}^{-1}$ in InP:Fe at around 970 nm. This enhancement was achieved by combining band-edge resonant nonlinearities with a second resonant enhancement derived from the bipolar transport in this material. Measurements of gain as a function of pump intensity, applied field, grating spacing, wavelength, and temperature are presented. No moving gratings were required.

Photorefractive semiconductors have been a subject of great interest as they offer the possibility for use as fast optical signal processing components at near-infrared wavelengths.[1,2] However, they typically have small two-wave mixing gain coefficients even with externally applied fields. We have recently shown that in semiconductors near the band edge, refractive index change due to the Franz–Keldysh effect can be very large and can be used to enhance two-wave mixing gains over those obtained using the Pockels electro-optic effect alone.[3] Gains may be further increased by using methods such as the moving grating technique.[4] By using the moving grating technique, gain coefficients as high as 16.3 cm^{-1} were demonstrated in GaAs.[3] Here we present results of two-wave mixing gains in InP:Fe obtained by combining the electro-refractive photorefractive effect (ERPR) with the conventional Pockels electro-optic photorefractive effect (EOPR) near the band edge and enhancing the photorefractive space charge field through use of a newly reported temperature resonance technique.[5] No moving grating is required.

Mainguet[6] reported a gain of 4 cm^{-1} in InP:Fe using only dc electric fields and recently Picoli *et al.*[5] have pointed out that a strong resonance exists between intensity and temperature, resulting in an enhancement of the two-beam coupling gain. Using a dc field, gains as high as 11 cm^{-1} ($\lambda = 1.06\ \mu\text{m}$) were reported using EOPR and temperature stabilization in InP:Fe.[7] This new resonance mechanism of temperature stabilization offers a convenient method for improving gains since it requires the use of only a thermoelectric device and a dc field.

Two Czochralski-grown samples of InP:Fe were used in the study. Sample A had a length of 2.2 mm and an interelectrode distance of 1.5 mm. The room-temperature absorption spectrum for sample A is shown in Fig. 1 as the heavy line. Sample B had a length of 5 mm and an interelectrode spacing of 2 mm. The samples were placed between two copper electrodes, one of which was mounted on a thermoelectric cooler. Temperature was monitored with two thermocouples mounted at the edge of each electrode. The signal from the thermocouple mounted nearest to the cooler was used to provide feedback to the cooler's supply circuit in order to maintain a constant temperature. A tunable Ti:sapphire laser pumped by a 5 W, cw argon laser was used for the wave mixing experiments.

Data were taken using a standard two-beam coupling arrangement. The grating vector and applied field were both parallel to the ⟨100⟩ axis. With the beams polarized normal to the plane of incidence (⟨110⟩) both the EOPR and ERPR effects were present and summed together, while when polarized parallel (⟨100⟩) only the ERPR effect was measured.[3]

The gain coefficient Γ was calculated by using[8]

$$\Gamma = \ln[\gamma\beta/(1-\gamma+\beta)]/L, \tag{1}$$

where γ is the ratio of the signal beam with and without the pump on, β is the pump-signal intensity ratio, and L is the interaction length. The grating spacing Λ is given by

$$\Lambda = \lambda/(2\sin\theta), \tag{2}$$

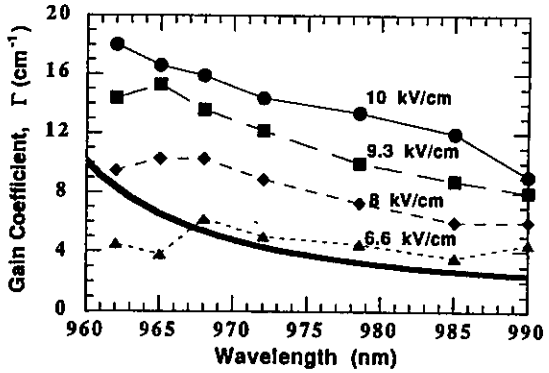

FIG. 1. Two-beam coupling gain coefficient as a function of wavelength for sample A. Intensity was adjusted at each point to achieve maximum gain ($\beta = 1000$). Room-temperature absorption is shown as the heavy line.

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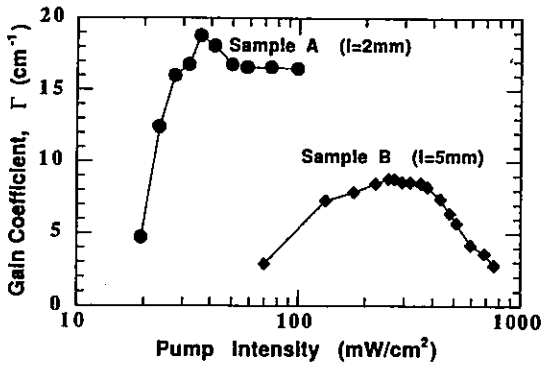

FIG. 2. Gain coefficient as a function of pump intensity with $E_0 = 10$ kV/cm, $\beta = 1000$, Sample A, $\lambda = 962$ nm, $\Lambda = 5$ μm, $T = 14.5$ °C; sample B, $\lambda = 972$ nm, $\Lambda = 3.3$ μm, $T = 18$ °C.

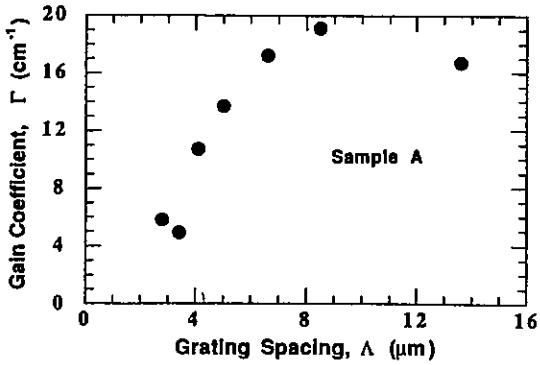

FIG. 3. Gain coefficient as a function of grating spacing for sample $\lambda = 970$ nm, $T = 17$ °C, $\beta = 1000$, $E_0 = 10$ kV/cm.

where θ is the outside half-angle between the two beams and λ is the free-space wavelength.

The maximum gain coefficient measured from both ERPR and EOPR was 19 ± 2 cm^{-1} ($\lambda = 970$ nm, $\Lambda = 8.5$ μm, $T = 17$ °C, $E_0 = 10$ kV/cm, $I_p = 70$ mW/cm^2, $\beta = 1000$, where E_0 is the applied electric field and I_p is the pump beam intensity). This corresponds to an intensity modulation of 70 times in our 2.2-mm-long crystal in response to the pump beam. At this wavelength the absorption coefficient was 5 cm^{-1}, yielding a net gain of 14 cm^{-1}. The gain measured due to ERPR alone, obtained by rotating the polarization of both beams parallel to the ⟨100⟩ axis, was 12 ± 2 cm^{-1}. As a check, the polarity of the applied field was reversed and a change in the coupling direction was observed. The change in coupling direction is consistent with ERPR.[3]

Figure 1 shows the gain coefficient as a function of wavelength and applied field for a fixed grating spacing of 5 μm and a temperature of 19 °C. The pump intensity was adjusted to achieve maximum gain at each wavelength. Both absorption and gain increase with photon energy (decreasing wavelength), producing a maximum net gain in the region 970–985 nm. The increase in gain near the band edge is characteristic of ERPR and was seen in GaAs.[3]

Figure 2 shows the gain coefficient versus pump intensity incident upon the crystal for both samples. The relatively constant gains in sample A at high intensity are most likely due to changes in the resonance conditions as the internal temperature rises due to Joule heating from the increase in photoconductivity with increasing incident power. Sample B clearly shows the expected resonance centered around 250 mW/cm^2. The lower gain coefficient measured in sample B may be due to the inability to maintain an optimum value of intensity over the full length of the absorbing sample.

The effect of grating spacing on gain coefficient at a fixed intensity and temperature is shown in Fig. 3. The gain coefficient increases rapidly with grating spacing and shows a maximum near $\Lambda = 9$ μm. This particular optimum should change with temperature, intensity and/or applied field.

In order for a temperature-dependent resonance in the photorefractive space-charge field to occur, the carriers sponsible for photoconductivity and dark conductiv must be of opposite sign.[7] In InP:Fe at 1.06 μm excitatic the majority photoexcited carriers are holes, while da conductivity is dominated by electrons. The photoioniz tion cross sections for electrons and holes in InP:Fe crease proportionally as the wavelength decreases fr $\lambda = 1.06$ μm towards the band edge.[9] Our measureme of the beam coupling energy transfer direction with appli field near the band edge were consistent with holes as bei the dominant photocarrier,[3] making it possible to apply t temperature stabilization technique near the band edge.

The gain coefficient measured is really an avera along the length of the crystal. Because of the moder absorption near the band edge and the resonance of ga with intensity, the peak gain coefficient, occurring son where inside the crystal, may be higher than the measur gain coefficient. For this reason it is likely that even larg gain coefficients can be measured using a thinner samp At long wavelengths, the temperature difference across t crystal was less than 2 °C, but at wavelengths closer to t band edge, where more light was absorbed, the differen increased to as much as 6 °C. This heating effect caused change in resonance conditions across the width of t crystal which may have limited the gains achieved. Wi more efficient cooling schemes, larger and more unifor heat dissipation should occur, resulting in smaller grac ents and possibly larger gains.

In summary, we have measured very large two-bea coupling gains ($\Gamma = 19$ cm^{-1}) in InP:Fe using the Fran Keldysh electrorefractive effect combined with temper ture stabilization. With the use of better temperature co trols and thinner samples even larger gain coefficients a expected. While the moving grating technique can be us with the combined effect of ERPR and EOPR to produ large two wave mixing gains,[3] it requires an elaborate set and is not useful for applications such as self-pump phase conjugation. The sample temperature stabilizatic technique for achieving large gains in InP requires only thermoelectric device and a dc voltage. When EOPR ar ERPR are combined, large gains at 970 nm can l achieved at a wavelength which is compatible wit

strained-layer lasers. This technique may find applications in phase locking of laser arrays, optical phase conjugation, and signal processing.

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