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PHOTOREFRACTIVE PROCESSES AT NEAR INFRARED WAVELENGTHS

Graeme W. Ross, Petr Hribek and Robert W. Eason

Optoelectronics Research Centre and Department of Physics,
University of Southampton, Southampton, SO9 5NH, UK.

I Photorefractive Phase Conjugation

Phase conjugation using photorefractive crystals has found many applications in areas such as optical processing and distortion correction. The simplest and most elegant configuration (self-pumped phase conjugation, SPPC) allows phase conjugation without the need for additional optics - a single laser beam incident upon a cut, polished crystal induces a refractive index grating which in turn diffracts light to generate the precise phase conjugate of the incident beam. Observation of the effect has been carried out mainly in the visible part of the spectrum where crystal response has tended to be most efficient. However, with the availability of diode lasers operating at near infrared wavelengths, recent attention has been drawn to the possibility of extending the crystal response to allow observation of SPPC and other photorefractive processes at diode compatible wavelengths. Efficient SPPC has already been observed with reflectivities as high as 72% at 800nm, using a nominally undoped crystal of photorefractive $BaTiO_3$, and there has been a concerted effort to extend and enhance the response in the near infrared region via the addition of different dopants.

Experiments to assess phase conjugation at near infrared wavelengths were carried out on a crystal supplied by Sandoz Huningue S.A., France, and a comparison was made with a nominally undoped sample of $BaTiO_3$[1].

The Sandoz $BaTiO_3$ crystal used was grown by the top-seeded solution growth technique from 99.999% purity starting materials, annealed and electrically poled. An unknown accidental impurity produced an enhanced absorption in the red and near infrared with an absorption peak at about 640nm that gave the crystal a blue colour. The absorption spectrum measurement (Fig. 1) for this crystal was performed with a Perkin-Elmer Lambda 9 spectrometer using randomly polarized light perpendicular to the c-axis.

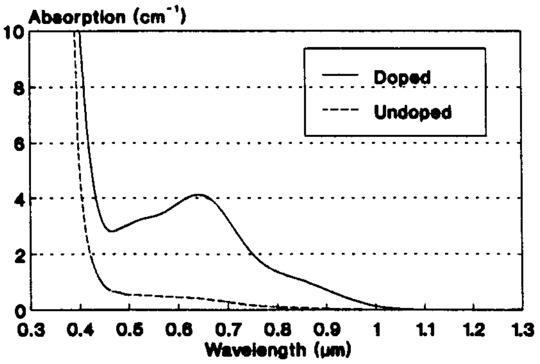

Fig 1 Absorption spectra of doped and undoped $BaTiO_3$ using randomly polarised light

With the crystal mounted in air on a combined rotation-translation stage, a systematic study was undertaken to assess the phase conjugate reflectivity with respect to wavelength, horizontal beam position on the entrance face, external angle of incidence and input power. A Ti:sapphire laser pumped using a 5W argon laser, and calibrated using an Anritsu optical spectrum analyser, was used to provide a tunable source of infrared radiation.

Phase conjugation was optimised by rotating the crystal to Brewster's angle (~ 67°, as in Ref. 1) to both minimise the Fresnel reflection and also maximise access to the largest electro-optic coefficient. Fig. 2 compares the wavelength response of the doped and undoped samples.

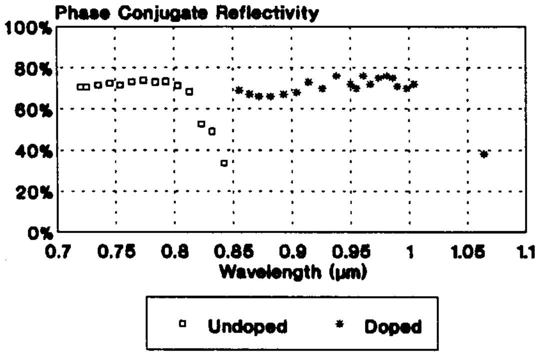

Fig 2 Phase conjugate reflectivity against wavelength

The response time of the process in the blue crystal was measured over the range 7mW to 70mW at 800nm, where we define response time as the time taken for the phase conjugate signal to rise from 10% to 90% of its saturated value. Typical response times at intensities of ~1Wcm^{-2} were ~100s. After each measurement the crystal was uniformly illuminated for 2 minutes using a 75W white light source to ensure that all gratings were erased. Data suggested that the response time is proportional to I_a^{-x} where x = 0.75 - a sublinear relationship indicating, perhaps, the presence of shallow traps in the photorefractive mechanism.[2]

The unexpectedly high infrared reflectivity of the blue crystal (given the high absorption) raises questions regarding the photorefractive mechanism responsible. If we assume that the beam is totally internally back reflected from the crystal faces to form transmission refractive index gratings, the crystal absorption and the round-trip path length, in fact, imply a maximum reflectivity of up to a factor of four less than that observed. This inconsistency implies that, in the absence of significant light induced transparency, reflection gratings near the entrance face of the crystal may perhaps be responsible for the high reflectivities by a backward scattering mechanism[3].

During the course of the experiments, it also was found that instabilities in the phase conjugate reflectivity could be removed by vibrating the crystal slightly. Further investigations are currently under way, as are investigations into the instability suppression, and the species responsible for the enhanced infrared response.

Summary I :

- Phase conjugation (possibly due to stimulated backscattering) at near infrared wavelengths
- Reflectivities of up to 76% at 1µm and 38% at 1.064µm
- Laser diode compatibility
- Vibration stabilisation

II Incoherent Beam Coupling

Beam coupling using the class of mutually pumped phase conjugators in photorefractive materials has recently become a subject of great interest as a method of forming a holographic link between two mutually incoherent, even independent, laser sources. The beam coupling interaction within the photorefractive crystal may be explained by the sharing of fanning gratings, with automatic Bragg matching allowing a self-reinforcing, self-aligning interconnect to form between the two sources. In this way, phase conjugates of both beams are generated simultaneously : diffracted light from source 1 forms the phase conjugate of beam 2 (hence the source of photons for the phase conjugate of beam 2 is beam 1, and vice versa) permitting the exchange of spatial information without cross-talk. Several geometries exist for incoherent beam coupling, however, an interesting feature of the Double Phase Conjugate Mirror (DPCM) geometry[4] (Fig. 3) is the possibility of gain as previously demonstrated at 488nm by Fischer et al.[5] In this section, we examine gain using the DPCM at near infrared wavelengths, and utilise the wavelength tolerance of the DPCM geometry (the Double Colour Pumped Oscillator - DCPO[5]) to aid coupling between two separate lasers.

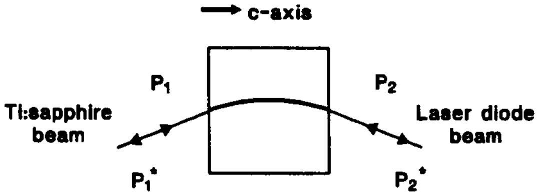

Fig 3 Incoherent beam coupling

The crystal used in our experiment was a 6mm cube of nominally undoped $BaTiO_3$ which has been shown previously to exhibit favourable response[1] at near infrared wavelengths. The lower absorption compared to that of the doped sample (Fig. 1) consequently means that the undoped crystal has a higher transmission which is advantageous here : a high transmission means efficient coupling of the two sources.

In our experiment[6], a laser diode and a Ti:sapphire laser were used to provide the mutually incoherent beams. The laser diode was a SHARP LT017 AlGaAs device operating single longitudinal mode at around 808nm. The laser diode beam (~5.8mW) was incident on the +c face of the photorefractive crystal (Fig. 3) and light from the Ti:sapphire laser (tuned to approximately the same nominal wavelength as the laser diode) was incident on the -c face of the crystal. A variable neutral density filter placed in the path of the Ti:sapphire beam allowed the incident power ratio of Ti:sapphire to laser diode at the crystal ($r = P_1 / P_2$) to be adjusted. Fig. 4 shows the effective laser diode reflectivity ($R = P_2^* / P_2$) of the crystal for different incident power ratios (r). It can be seen from Fig. 4 that $R > 1$ for the range $\sim 3 < r < \sim 80$, and the curve exhibits the characteristic shape predicted theoretically and observed experimentally by Fischer et al.[5] in their DPCM experiments. The maximum reflectivity of ≥ 6, which to our knowledge is the highest reported to date at near infrared wavelengths, occurs with an incident power ratio of $r \sim 23$.

The wavelength of the DCPO configuration was then examined by measuring the transmission ($T = P_2^* / P_1$) as a function of Ti:sapphire wavelength. The results demonstrate that transmission is greatest (~0.3) for a range of wavelengths spanning ~15nm around the nominal diode wavelength. This maximum transmission is likely to occur when both sources are of the same wavelength (allowing precise Bragg matching) and implies that perhaps the wavelengths of the two sources are matched over this region.

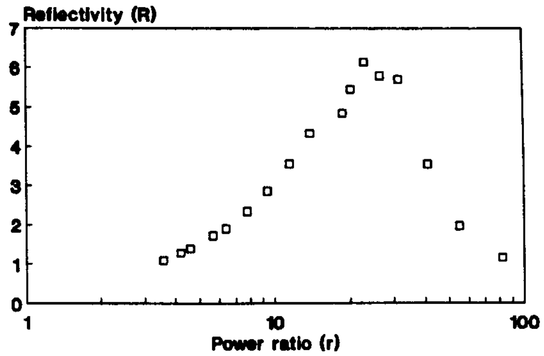

Fig 4 Graph of phase conjugate reflectivity against incident power ratio

This would in turn imply that light channelled from the Ti:sapphire laser into the laser diode facet by the DCPO influences the lasing characteristics of the laser diode by forcing it to lase at the Ti:sapphire wavelength. In order to confirm this, and also to assess the effects of feedback into the diode, an Anritsu optical spectrum analyser was used to monitor the laser diode wavelength as a function of Ti:sapphire wavelength. In the range 800nm to 814nm, it was found that when the injected Ti:sapphire wavelength corresponded to a longitudinal mode of the laser diode, the diode lased single mode at the injected Ti:sapphire wavelength, and the diode mode spacing was confirmed to be 0.33nm. Fig. 5 shows the diode wavelength for a selection of such injected Ti:sapphire wavelengths.

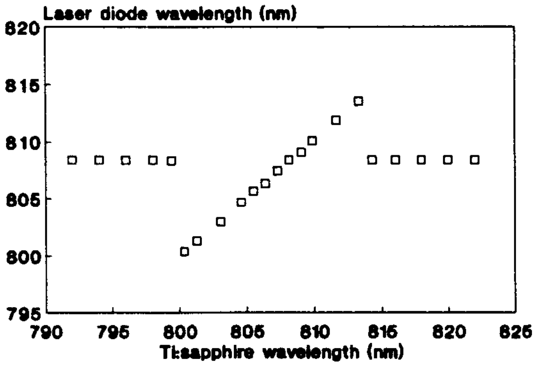

Fig 5 Laser diode wavelength against Ti:sapphire wavelength

At wavelengths outside the range 800nm to 814nm, the laser diode was unaffected by the Ti:sapphire. The region in which the laser diode wavelength follows closely that of the Ti:sapphire, corresponds to the region of maximum ~0.3 transmission. It would seem that the main factor influencing the width of this region is the laser diode gain bandwidth : outside this region, the laser diode cannot support the lasing wavelength imposed by the Ti:sapphire and instead relaxes to its nominal wavelength, at which point the fraction of Ti:sapphire signal injected into the diode facet is reduced by the angular offset due to the DCPO Bragg selection.

Summary II :

- Phase conjugation with gain : reflectivity of 600%
- Infrared operation (laser diode compatibility)
- No coherence requirement
- Wavelength tolerance
- Laser diode tuning

III Phase conjugate fibre laser

Phase conjugate optics have also been used as external mirrors providing feedback for systems such as dye and Argon ion lasers[7] by photorefractive four-wave mixing. Once initiated, the phase conjugate process may become self-sustaining by the lasing action. In this section we report feedback into a multimode optical fibre amplifier to demonstrate lasing[8]. Work was initially motivated by the idea of forming a double-pass amplifier using phase conjugate feedback. Correction of polarisation and modal scrambling in passive multimode fibre has already been demonstrated using phase conjugation[9]. It was found in our earlier work, however, that the expected gain observed in the fluorozirconate fibre used was too low for efficient brightness enhancement due to signal saturation. However, during the course of the investigation, it was found that it was possible to form a laser cavity with the fibre as the amplifying medium and a passive phase conjugate mirror acting as one of the reflectors.

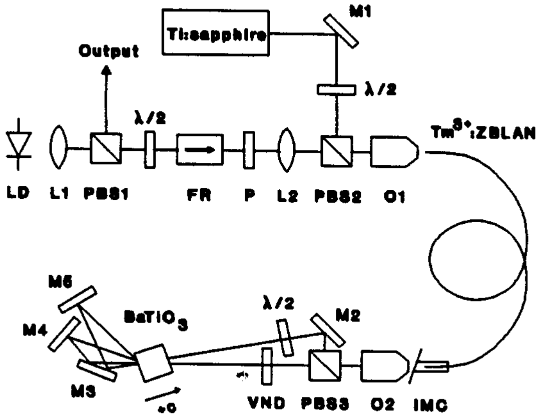

Fig 6 Experimental arrangement. LD laser diode; L's lenses; PBS's polarising beam splitters; FR Faraday rotator; P polariser; O's microscope objectives; IMC index-matching cell; VND variable neutral density filter; M's mirrors

Our experimental arrangement is shown in Fig. 6. The injected signal was provided by a SHARP LT017 single stripe AlGaAs laser diode operating single longitudinal mode at ~808nm at room temperature and isolated using a Faraday rotator and polariser. The amplifying medium was a 6m length of fluorozirconate fibre of the standard ZBLAN composition doped with 500ppm by weight of Tm^{3+} ions. It has been demonstrated by Carter et. al.[10], that efficient laser action and high small-signal amplification between 805nm and 830nm can be achieved by pumping this system at 785nm, with a possible single pass gain at 806nm of ~20dB for a 6m length of fibre. This amplification range ensured the compatibility of the AlGaAs laser diode, the ZBLAN fibre and the $BaTiO_3$ crystal. The pump wavelength was also chosen because of its compatibility with AlGaAs semiconductor diode lasers, although for our initial experiment the pump power was provided by a Ti:sapphire laser. Phase conjugation was achieved using the undoped 6mm cube of photorefractive $BaTiO_3$ in a ring configuration - an arrangement useful for phase conjugating small signals. Reflectivities of up to 22% (uncorrected for Fresnel reflection) have been measured with this particular crystal in the ring configuration using e-polarised light at 808nm.

Initially, with no grating present in the crystal and with only pump light incident on the fibre, no lasing was observed as the fluorescent output from the fibre was insufficient for grating formation due to its large spectral bandwidth. With the laser diode signal injected, however, the ring conjugator was established after a few seconds and lasing in the fibre was observed. The lasing wavelength was determined using an Anritsu optical spectrum analyser and found to match that of the laser diode to within the 0.1nm resolution of the analyser.

When the laser diode signal was then blocked, the photorefractive grating persisted and the fibre continued to lase. Blocking the phase conjugate feedback ring prevented lasing and confirmed that the photorefractive grating was indeed providing the feedback mechanism into the fibre. The 4% Fresnel reflection at the un-matched end of the fibre completed the laser resonator. Lasing occurred only when the incident pump light was greater than ~600mW. The lasing wavelength (808.1nm) was closely matched to that of the laser diode, but appeared to be at a wavelength corresponding to a mode adjacent to the fundamental operating wavelength of the diode (807.7nm) within the resolution limits of the spectrum analyser. The wavelength tended to be unstable, however, as lasing was also observed at wavelengths corresponding to the fundamental diode wavelength and at shorter wavelengths. The timescale of these changes (a few seconds) would suggest a grating competition process within the photorefractive crystal and implies perhaps that gratings are written by the diode not only by the fundamental diode wavelength, but also by the adjacent modes amplified on a single pass through the fibre.

A simple analysis using the Kogelnik model[11] - regarding the bandwidth of a single sinusoidal transmission grating of period 1.6μm and length 6mm - indicates a FWHM diffraction bandwidth of ~2nm centred on the Bragg-matched wavelength. This would confirm that one single grating would be capable of providing feedback of fluorescent emission from the fibre over this range of wavelengths. Reasons as to why laser operation does not remain at the fundamental diode wavelength (which would be expected to yield the strongest grating which would be reinforced in turn by the lasing action) have not, as yet, been determined. Methods of achieving stable single frequency operation are under further investigation as are experiments on tunability by crystal rotation and externally-applied electric field.

Summary III :

- Self-sustaining phase conjugate feedback into a fluorozirconate fibre amplifier allowing laser action in the near infrared

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