Phase-conjugate fluorozirconate fiber laser operating at 800 nm

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We report phase-conjugate feedback into a fluorozirconate optical fiber amplifier at infrared wavelengths. By using a semiconductor laser diode at 807 nm, a grating is established in photorefractive $BaTiO_3$ that, in the ring configuration, provides feedback into the amplifier necessary for laser action. Once written, the grating is self-sustaining, and lasing is observed even after the laser diode is removed.

Phase-conjugate optics have been used as external mirrors to provide feedback for systems such as dye[1] and argon-ion[2] lasers by photorefractive four-wave mixing. Once initiated, the phase-conjugate process may become self-sustaining by the lasing action. In this Letter we report feedback into a multimode optical fiber amplifier to demonstrate lasing. Research was initially motivated by the idea of forming a double-pass amplifier by using phase-conjugate feedback. Correction of polarization and modal scrambling in passive multimode fiber has already been demonstrated by using phase conjugation.[3] It was found in our earlier research, however, that the expected gain observed in the fluorozirconate fiber used was too low for efficient brightness enhancement owing to signal saturation. However, during the course of the investigation, it was found that it was possible to form a laser cavity with the fiber as the amplifying medium and a passive phase-conjugate mirror acting as one of the reflectors.

Our experimental arrangement is shown in Fig. 1. The injected signal was provided by a Sharp LT017 single-stripe AlGaAs laser diode operating single longitudinal mode at ~807 nm at room temperature and isolated using a Faraday rotator and polarizer. The amplifying medium was a 6-m length of fluorozirconate fiber of the standard ZBLAN composition ($53ZrF_4-20BaF_2-4LaF_3-3AlF_3-20NaF$, in mol. %) doped with 500 parts in 10^6 by weight of Tm^{3+} ions. It has been demonstrated by Carter *et al.*[4] that efficient laser action and high small-signal amplification between 805 and 830 nm can be achieved by pumping this system at 785 nm, with a possible single-pass gain at 806 nm of ~20 dB for a 6-m length of fiber. This amplification range ensured the compatibility of the AlGaAs laser diode, the ZBLAN fiber, 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. The transition was operated as a quasi-three-level scheme with in-band pumping of the upper laser level ($^3F_4$). Owing to this resonant pumping scheme, a full inversion was never possible (the maximum inversion being ~60%), and a significant ion population would always remain in the ground state ($^3H_6$). The core diameter of 10 μm and the numerical aperture of 0.15 implied that this fiber was multimode at both the signal and pump wavelengths. The pump and signal were polarized orthogonally and combined at polarizing beam splitter PBS2 and launched into the fiber with a 10× microscope objective. The output end of the fiber was held in an index-matching cell to prevent lasing off the cleaved fiber end by suppressing the 4% Fresnel reflection. The signal power incident upon the launch objective was ~30 mW. Using the fiber cutback technique, we found the diode launch efficiency to be ~60%, which would imply ~18 mW of launched power. Assuming a launch efficiency greater than this for the Ti:sapphire beam, the incident pump power of ~700 mW would correspond

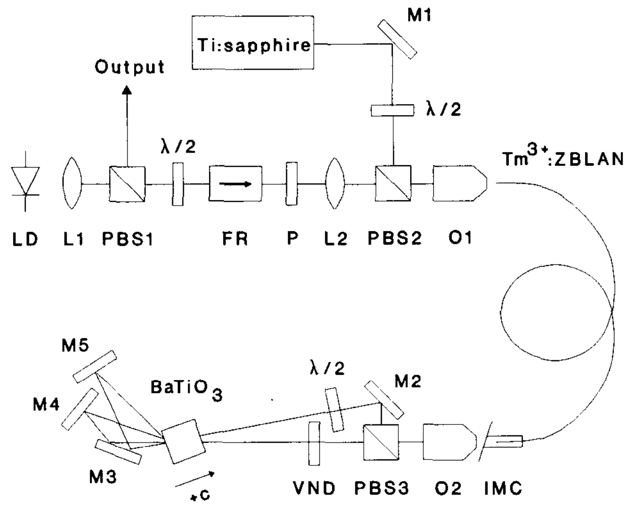

Fig. 1. Experimental arrangement. LD, laser diode; L1, lens (focal length 6.5 mm); PBS's, polarizing beam splitters; FR, Faraday rotator; P, polarizer; L2, lens (focal length 100 mm); O1, 10× microscope objective; O2, 20× microscope objective; IMC, index-matching cell; VND, variable neutral-density filter; M's, mirrors.

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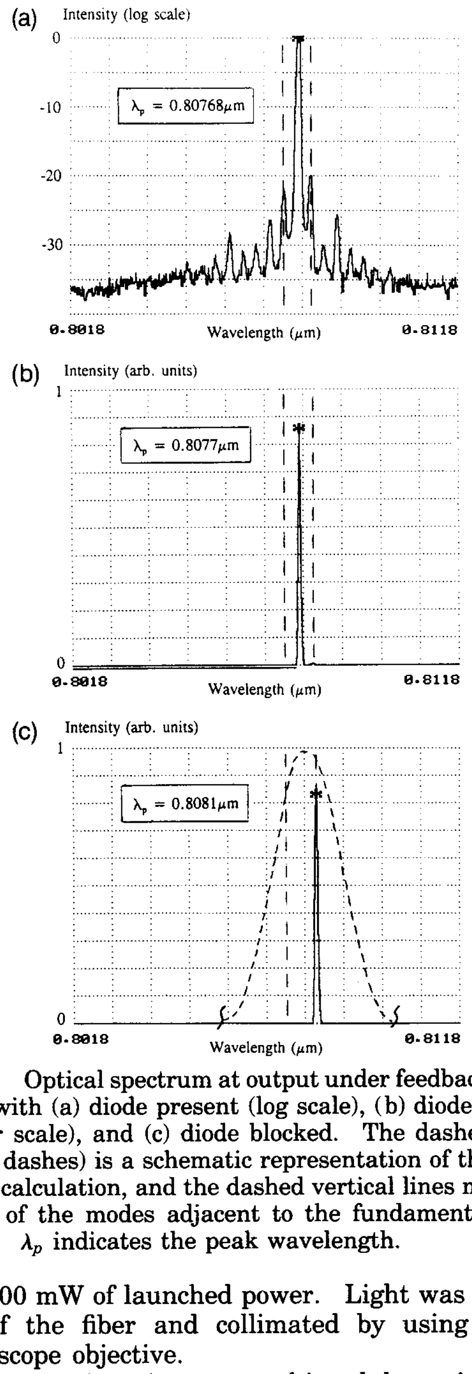

Fig. 2. Optical spectrum at output under feedback conditions with (a) diode present (log scale), (b) diode present (linear scale), and (c) diode blocked. The dashed curve (short dashes) is a schematic representation of the bandwidth calculation, and the dashed vertical lines mark the peaks of the modes adjacent to the fundamental diode mode. λ_p indicates the peak wavelength.

to >400 mW of launched power. Light was coupled out of the fiber and collimated by using a 20× microscope objective.

Phase conjugation was achieved by using a 6-mm cube of photorefractive $BaTiO_3$ in the ring configuration. Reflectivities of as much as 22% (uncorrected for Fresnel reflection) have been measured with this particular crystal in the ring configuration using *e*-polarized light at 807 nm. Typical rise times at intensities of ~1 W/cm^2 were ~5 s. Collimated light from the fiber was separated into *e*- and *o*-polarization components using polarizing beam splitter PBS3, and the *o* component was rotated through 90° by using a half-wave plate in order to access the large r_{42} electro-optic coefficient and allow phase conjugation. Light entered the $+c$ face of the crystal, which was tilted at ~30° to the incident *e*-component direction. The external loop angle was also ~30°, chosen to optimize reflectivity. The two four-wave mixing regions were generated at the top and bottom of the crystal with a slight overlap. The variable neutral-density filter was included to ensure similar reflectivities of both polarization components. It was found that stronger phase-conjugate reflectivities were obtained if the two regions did not completely overlap in the crystal volume. However, instabilities of the output would suggest a grating competition process between the regions or, perhaps, incomplete phase locking of the two components, which would lead to incorrect reconstruction at the beam splitter. Phase-conjugate output tended to be more stable with only one component present.

To determine whether the fiber was lasing, an optical chopper was placed between beam splitter PBS2 and microscope objective O1, and the output was monitored for relaxation oscillations by using a silicon detector connected to an oscilloscope.

Initially, with no grating present in the crystal and with only pump light incident upon the fiber, no lasing was observed, as the fluorescent output from the fiber was insufficient for grating formation owing to its large spectral bandwidth. With the laser-diode signal injected, however, the ring conjugator was established after a few seconds. Lasing was observed, and the lasing wavelength was determined by using an Anritsu optical spectrum analyzer. Figures 2(a) and 2(b) (log and linear scales, respectively) demonstrate that the lasing wavelength (λ_p) matches that of the laser diode to within the 0.1-nm resolution of the analyzer. Figure 2(a) also shows the other diode modes spaced at ~0.35 nm.

When the laser-diode signal was then blocked, the photorefractive grating persisted and the fiber 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 fiber. The 4% Fresnel reflection at the unmatched end of the fiber completed the laser resonator. Lasing occurred only when the incident pump light was greater than ~600 mW. From the calibrated trace [Fig. 2(c)] the lasing wavelength (808.1 nm) can be seen to be closely matched to that of the laser diode but appears to be at a wavelength corresponding to a mode adjacent to the fundamental operating wavelength of the diode (807.7 nm) within the resolution limits of the spectrum analyzer. 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 time scale 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 fiber. Using a beam profile, we observed single- and double-lobed structures at the output; however, a phase-conjugate replica of the laser diode was not obtained owing, we believe, to the lasing action. The instabilities mentioned did not permit measurement of the laser slope efficiency.

A simple analysis with the Kogelnik model[5]—regarding the bandwidth of a single sinusoidal transmission grating of period 1.6 μm and length 6 mm—indicates a FWHM diffraction bandwidth of

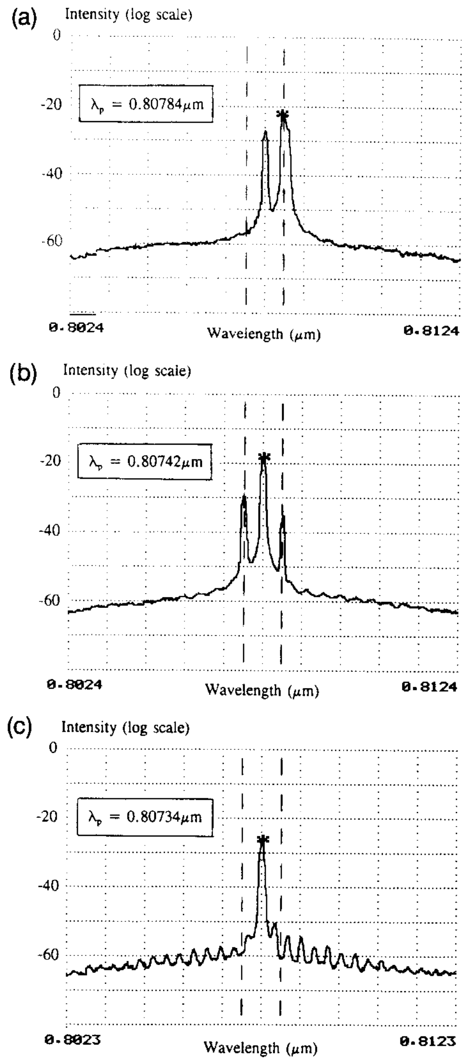

Fig. 3. (a) Optical spectrum at output under feedback conditions with diode blocked and with a notch filter in the ring cavity, and (b) the same arrangement 10 s later. Note the peak separation of ~0.5 nm. The dashed vertical lines mark peak positions. (c) Spectrum showing diode mode separation of ~35 nm. Note that the peaks in (a) and (b) do not appear to correspond to the modes of the laser diode. λ_p indicates the peak wavelength.

~2 nm centered on the Bragg-matched wavelength as indicated in Fig. 2(c). This would confirm that one single grating would be capable of providing feedback of fluorescent emission from the fiber 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 in turn be reinforced by the lasing action) have not, as yet, been determined. One possible explanation for this behavior has been discussed in Refs. 4 and 6 and concerns the effects of pump power density, fiber length, and also levels of feedback on the lasing wavelength obtained. The Tm^{3+} ZBLAN system in particular[4] will operate at a wavelength that depends on the overall cavity loss and implies that for a lower-loss cavity (i.e., higher feedback into the cavity) the fiber tends to lase toward longer wavelengths (perhaps coincidentally corresponding to a diode mode). Shifts toward the shorter wavelengths may be explained similarly by suggesting that slight erasure of the grating (due, maybe, to a change in the transverse mode structure) could decrease the feedback. As mentioned above, however, the wavelength was observed to move discretely, rather than continuously to different wavelengths. Reasons for this remain unclear.

When a notch filter (~5% transmitting at 785 nm and ~55% transmitting at 807 nm) was placed after microscope objective O2 to remove any residual pump, the lasing emission contained several discrete wavelength regions [Figs. 3(a) and 3(b); note the log scale]. As before, gratings were established by prewriting with the diode laser, which was then blocked. The lasing wavelength of the system again closely matched that of the injected laser-diode signal, but, as before, instabilities existed. Examination of the output indicates simultaneous wavelength bands spaced at ~0.5 nm, which appear to be spaced too far apart to correspond to those of the diode [Fig. 3(c) is included for comparison]. We suspect that an étalon effect which is due to the notch filter may be responsible for this behavior.

Reasons for the complex lasing behavior observed in the filtered and unfiltered cases remain unclear but may perhaps be due to a balance among (a) fluctuations in the reflectivity of the ring conjugator that are due to grating competition, (b) intensity-dependent gain of the fiber, and (c) the lasing/feedback relationship outlined above. The fact that the gratings are not completely erased when the diode is removed, however, certainly implies that the gratings (although not self-starting) are self-reinforcing.

In conclusion, we have demonstrated that a photorefractive grating written by using a laser diode at 807 nm is capable of providing self-sustaining phase-conjugate feedback into a fluorozirconate fiber amplifier to allow laser action. Methods of achieving stable single-frequency operation are under further investigation, as are experiments on tunability by crystal rotation and externally applied electric field.

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