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Er^{3+}:Yb^{3+}-codoped fiber distributed-feedback laser

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We report what is to our knowledge the first fiber distributed-feedback laser using a single Bragg grating at 1.5 μm written directly into a 2-cm-long Er^{3+}-doped fiber codoped with Yb^{3+}. We obtained robust single-frequency operation by either using one end reflector or locally heating the center of the grating to create the necessary phase shift.

Short, single-mode, Er^{3+}-doped fiber distributed-Bragg-reflector (DBR) lasers using photoinduced fiber-gratings[1,2] are promising alternatives to semiconductor DBR and distributed-feedback (DFB) lasers for use in high-capacity wavelength-division multiplexing communication systems as well as in CATV, lidar, fiber-optic sensor, and spectroscopy applications. Fiber DBR lasers are simple, fiber compatible, and scalable to high output powers, have kilohertz linewidths and low-intensity noise, and importantly are wavelength settable to within ~0.1 nm.

Er^{3+}-doped fiber DBR lasers are only robustly single frequency, provided that the grating bandwidth is kept below ~0.2 nm and the laser length is reduced to a few centimeters to increase the axial mode spacing. The pump absorption in Er^{3+} in such short laser lengths is normally only a few percent, and hence the slope efficiency of these lasers is very low (<1%), even when the maximum Er^{3+} concentration permitted by quenching considerations is used.[1] One can overcome this problem by codoping the Er^{3+}-doped fiber with Yb^{3+}, which increases the absorption at the pump wavelength by more than 2 orders of magnitude and permits close to quantum-limited efficiency operation of centimeter-long lasers.[3,4]

Unfortunately, the aluminophosphosilicate Er^{3+}:Yb^{3+}-codoped fiber used in the DBR experiment[4] was not photosensitive, and therefore the grating end reflectors had to be spliced to the doped fiber, introducing intracavity splice loss. However, recently we succeeded in writing a fiber grating with nearly 100% reflectivity directly in the same Er^{3+}:Yb^{3+}-codoped fiber by loading the fiber with hydrogen.[5] As a result we have now constructed what is to our knowledge the first fiber DFB laser in which the feedback is provided by a single fiber grating at 1.5 μm written into the amplifying fiber.

It is well known that a DFB laser with a uniform grating (i.e., not containing a phase shift) and no end reflectors will oscillate at two modes spaced symmetrically around the Bragg wavelength, as no real mode can exist in the DFB structure at the Bragg wavelength.[6] To obtain single-frequency operation of a DFB laser one can either use an end reflector to change the round-trip phase shift in the cavity[7] or introduce a single-pass optical phase shift of $\pi/2$ into the grating such that the round-trip phase condition is satisfied at the Bragg wavelength.[8] In this Letter we report both approaches.

The fiber DFB laser using a 100% end reflector is shown in Fig. 1(a). We butted the reflector against the fiber, using index-matching fluid. The total length of the Er^{3+}:Yb^{3+}-codoped fiber was 3 cm, the 2-cm-long photorefractive grating being at the reflector end. The refractive-index modulation Δn of the grating was 2.1×10^{-4}, yielding a grating strength κL of as much as 8.5 (in semiconductor DFB lasers κL is typically <3), where $\kappa = \pi \Delta n / \lambda_B$ is the grating coupling coefficient and L is the grating length. The FWHM reflection bandwidth was 0.37 nm, and the Bragg wavelength was 1535 nm. The fiber had Er^{3+} and Yb^{3+} concentrations of 1000 and 12,500 parts in 10^6, respectively, an N.A. of 0.2, and a cutoff wavelength of 1130 nm. The fiber was embedded in a glass capillary, and the output end was angle polished to prevent reflections. The laser was pumped by a 980-nm diode laser through the reflector, which transmitted 97% of the pump light.

The laser characteristics are shown in Fig. 2. The threshold pump power was 15 mW, and the slope efficiency at high pump power was 3.4%. The gradually increasing slope at low pump powers is probably due to the 1-cm-long section of Er^{3+}:Yb^{3+}-doped fiber

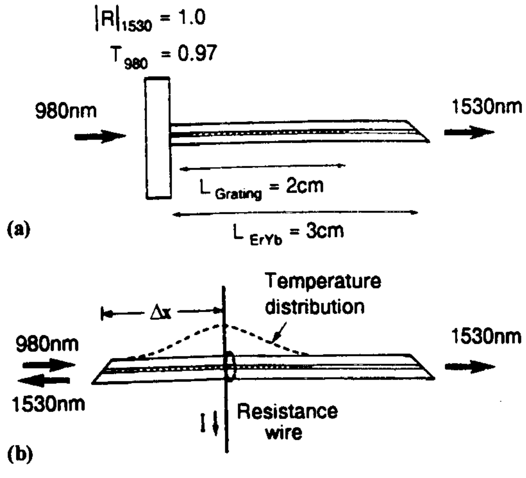

Fig. 1. Schematic illustration of an Er^{3+}:Yb^{3+}-codoped fiber DFB laser with (a) a non-phase-shifted grating with one 100% end reflector and (b) a (temperature) phase-shifted grating with no end reflectors.

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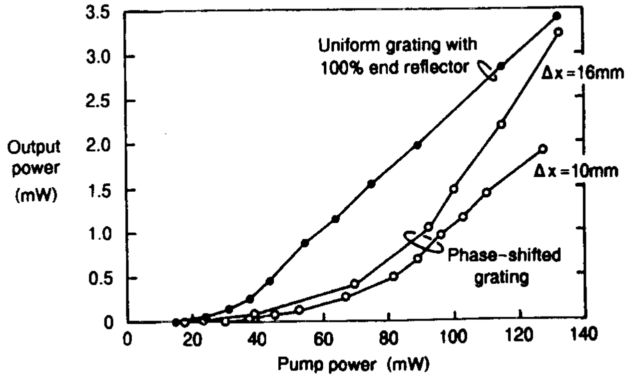

Fig. 2. Laser characteristics of a fiber DFB laser with a non-phase-shifted (uniform) grating with one 100% end reflector and a phase-shifted grating with no end reflectors. Δx is the position of the hot resistance wire relative to the input end of the grating.

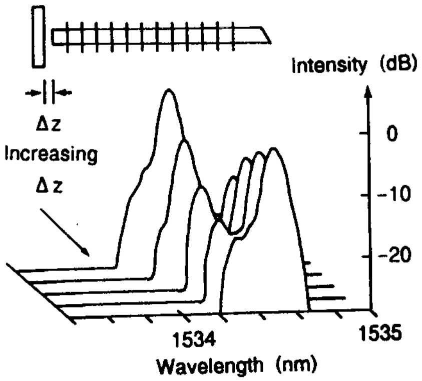

Fig. 3. Optical spectrum of the mirrored DFB laser for increasing separation Δz between the mirror and the grating. Δz varies from ~0 to ~$\lambda/4n$ (0.26 μm), where $n = 1.5$ is the refractive index of the index-matching fluid.

at the output end, which at low pump power acts as an absorber and at higher pump powers acts as an amplifier. Note that lasing could occur without the mirror, i.e., with a 4% end reflector but with much higher threshold.

The optical spectrum normally had two peaks, as expected for a non-phase-shifted DFB laser. However, the relative power in each of the two modes depended on the position (phase) of the mirror relative to the fiber grating,[7] as shown in Fig. 3, and at the appropriate phase shifts single-frequency operation was observed. The separation between the two modes is ~0.25 nm (32 GHz), in close agreement with the theoretical prediction of 0.23 nm (with $\kappa L = 8.5$).[6]

The phase-shifted fiber DFB laser configuration is shown in Fig. 1(b). The grating was the same as that used in the mirrored fiber DFB laser but without the end reflector. We introduced the phase shift within the grating by locally heating it, using a 2-cm-long, 0.2-mm-thick electrical resistance wire (0.46 Ω/cm) wrapped once around the glass capillary at a point Δx mm from the input end of the grating. The electrical current through the wire was typically 300 mA. Locally heating the grating slightly increases its refractive index around that point and so introduces the required optical phase shift.[9]

Without the phase shift present (and with no end reflectors) no lasing was observed. The laser power from the output end with an optimum phase shift at the center of the grating ($\Delta x \approx 10$ mm) is plotted in Fig. 2. The threshold pump power was 30 mW, and the slope efficiency at high pump power was again 3.4%. The output power from the input and output ends was measured and found to be similar. Moving the hot wire (and hence the phase shift and the intracavity intensity peak) toward the output end increased the ratio of emission from the output and input end, in agreement with results reported in Ref. 10 for a semiconductor DFB laser. With Δx = 16–18 mm the ratio was 4–6. In this case the maximum output power was 3.2 mW, with a threshold pump power and a slope efficiency of 18 mW and 5.4%, respectively (see Fig. 2).

The laser was always single mode, as shown in Fig. 4(a). However, both the orthogonal plane-polarized polarization states (separated by 1.85 GHz) of the laser mode oscillated, the differential power being 9 dB as measured with a linear polarizer at the output. The output polarization was independent of the pump polarization state. Figure 4(b) shows the spectrum obtained with increasing wire temperature and hence with increasing phase shift. The laser output is observed to increase from zero to a maximum (optimum phase shift) and then decrease again. As expected, the wavelength increases with increasing temperature.

The laser linewidth was measured with a 25-km-long self-heterodyne delay line. In single-mode operation the optical linewidth of the mirrored DFB laser was 60 kHz, whereas the linewidth of the phase-shifted DFB laser was 300 kHz. In both cases the

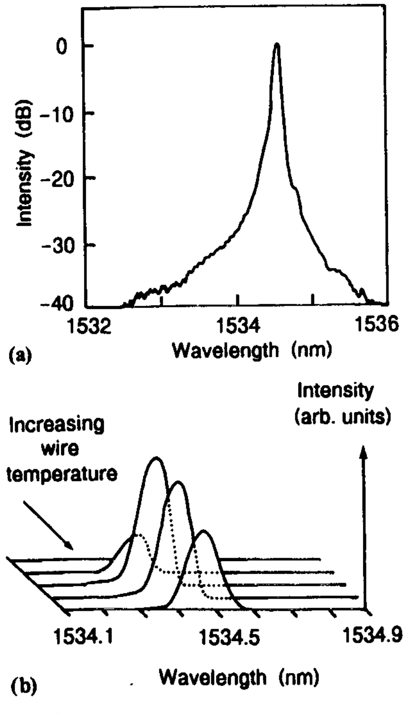

Fig. 4. Optical spectrum of a (temperature) phase-shifted fiber DFB laser (a) at maximum power with optimum phase shift and (b) for increasing wire temperature (and phase shift).

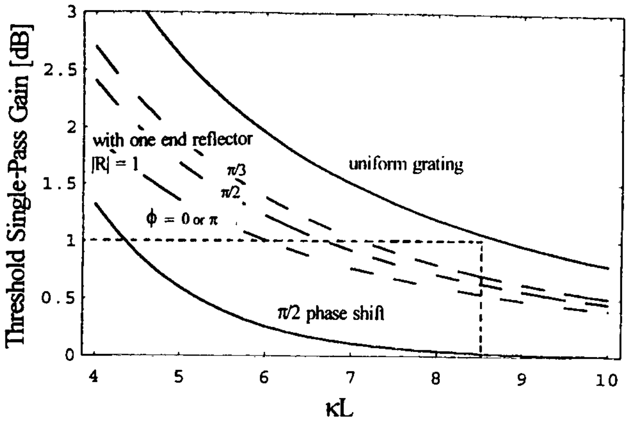

Fig. 5. Theoretical threshold single-pass net gain of the fundamental mode of a fiber DFB laser with uniformly distributed gain as a function of grating strength with a non-phase-shifted (uniform) grating, a non-phase-shifted grating with one 100% end reflector (for various values of the reflection phase ϕ), and a $\pi/2$ phase-shifted grating.

linewidth was independent of the output power. The relative intensity noise with 2-mW output power was <-150 dB/Hz for the mirrored DFB laser and <-143 dB/Hz for the phase-shifted DFB laser (above 40 MHz). The relative-intensity-noise spectra had maxima (-107 and -92 dB/Hz, respectively) at the relaxation oscillation frequency, which for both lasers was approximately 1.5 MHz.

Using the results in Refs. 6–8, we have calculated the theoretical threshold single-pass net gain required for the fundamental mode of various fiber DFB lasers as a function of the grating strength κL, assuming a *uniformly* distributed gain. The results are plotted in Fig. 5 for a non-phase-shifted DFB laser with no end reflectors, a non-phase-shifted DFB laser with one 100% end reflector, and a $\pi/2$ phase-shifted DFB laser. As is well known, Fig. 5 shows that a phase-shifted DFB laser has theoretically a significantly lower threshold gain requirement than a non-phase-shifted DFB laser (with or without an end reflector). The similar threshold observed in our experiment is believed to be due to the strongly *nonuniform* pump-power distribution along the cavity, which gives a population inversion that overlaps better with the laser intensity distribution in the mirrored DFB laser than in the phase-shifted DFB laser.

In the case of a non-phase-shifted DFB laser with one end reflector, the threshold gain is significantly lower than without an end reflector but depends on the phase relationship between the reflector and the grating, as Fig. 5 shows. Note that for a reflection phase $\phi = 0$ or π the reflector images the grating such that for a given κL the threshold gain is half that obtained without an end reflector. Our Er^{3+}:Yb^{3-} fiber had a maximum (i.e., fully inverted) gain of 0.5 dB/cm at 1535 nm (and of ~0.25 dB/cm at 1550 nm). Thus, with a cavity length of 2 cm and assuming no absorption or scattering loss, lasing is predicted in DFB resonator designs at 1535 nm with a threshold single-pass gain requirement of less than ~1 dB. For a grating strength of $\kappa L = 8.5$, Fig. 5 shows that lasing should therefore occur with either a 100% reflector or a grating phase shift but not with a non-phase-shifted grating having no end reflectors, an observation that is in agreement with our results.

The slope efficiency of the demonstrated fiber DFB lasers is low relative to that of the 2-cm-long DBR laser reported in Ref. 4, which had an overall slope efficiency of 22%. The main reason for this is the overly strong grating used in our experiment, which gives a nonoptimal laser output coupling and consequently a reduction in slope efficiency.

It is clear that optimization of the fiber DFB laser will lead to considerably improved performance relative to these first results. For example, Fig. 5 shows that, in the case of the phase-shifted laser, κ can be reduced by ~50% and still provide enough feedback to reach threshold. This will increase the slope efficiency by increasing the output coupling relative to the background loss. A weaker grating should also have lower intrinsic loss. Note that κ can be reduced even further if L is increased, which does not compromise the single-frequency performance but has the merit of increasing the available gain (i.e., $L \times 0.5$ dB/cm).

In conclusion, we have demonstrated a diode-pumped fiber DFB laser. Such a laser should have all the advantages of a fiber DBR laser but with the wavelength uniquely determined by one single grating.

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