Tunable, continuous-wave neodymium-doped monomode-fiber laser operating at 0.900–0.945 and 1.070–1.135 μm

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A tunable Nd^{3+}-doped monomode-fiber laser has been constructed that operates continuously at room temperature. The tuning range covered is 0.900–0.945 and 1.070–1.135 μm. Output powers of 3 mW for 53 mW of absorbed pump and 2 mW for 35 mW of absorbed pump, respectively, were achieved for the two ranges from pumping by a dye laser operating at 590 nm.

Efficient continuous-wave and pulsed fiber lasers[1–4] were recently developed by doping rare-earth ions into low-loss, monomode silica fibers using a modified chemical-vapor-deposition technique.[5] The small transverse dimensions of the fiber permit effective conduction of heat from the fiber, so that the thermal fracture and birefringence problems encountered in bulk glass lasers are eliminated. This has permitted continuous-wave operation, even on three-level laser transitions such as ${}^4I_{13/2}$–${}^4I_{15/2}$ in Er^{3+}-doped glass[2] and ${}^4F_{3/2}$–${}^4I_{9/2}$ in Nd^{3+}-doped glass,[6] which have hitherto not shown cw operation. The broad emission lines of impurity ions in glass offer the possibility of a wide tuning range, suggesting that fiber lasers may prove to be an important new class of tunable laser. They do not suffer the disadvantage of poor photochemical stability shown by many near-infrared dyes, nor do they need low-temperature operation, a feature of near-infrared color-center lasers and vibronic lasers. To assess their potential as tunable lasers, we have investigated their tuning behavior and, in view of the inhomogeneous broadening of the laser transitions, we have investigated the efficiency that can be obtained under narrow-linewidth operation. In this Letter we report the results of these investigations for Nd^{3+}-doped fiber. We have observed tuning ranges of 0.900 to 0.945 μm (${}^4F_{3/2}$–${}^4I_{9/2}$ transition) and 1.070 to 1.135 μm (${}^4F_{3/2}$–${}^4I_{11/2}$ transition) with conversion efficiency from the pump laser of up to 6% for an output linewidth of 0.06 nm. Attempts were also made to achieve operation at ~1.3 μm on the ${}^4F_{3/2}$–${}^4I_{13/2}$ transition, without success. Evidence points to an excited-state absorption preventing laser operation.

The general cavity arrangement of the tunable-fiber laser is shown in Fig. 1. A cw dye laser operating in the region of 590 nm was used as the pump source. This laser was launched through a high-reflectivity mirror of 3-mm thickness, which was butted against the cleaved end of a Nd^{3+}-doped monomode fiber of numerical aperture 0.2 and Nd^{3+} concentration of 300 parts in 10^6. The length of fiber used was chosen to optimize the performance at the operating wavelength and ranged from 1 to 2 m. Launch efficiency into the fiber was estimated to be ~40%. Better launch efficiency could probably be achieved if a thinner mirror substrate was used, thus reducing the spherical aberration. The output of the fiber passed through a 10× microscope objective and propagated, in a collimated beam, to the plane output coupler. Étalon effects between the fiber end face and the objective were much in evidence. A long-working-distance objective (8 mm) reduced this effect. The distance between the collimating objective and the output coupler was typically 30 cm, thus permitting the insertion of frequency-selective elements into the cavity.

Tuning of a fiber laser was previously achieved by using a grating as the frequency selector.[2] For this work we have used two- and three-plate birefringent filters as supplied for a cw dye laser (Coherent). The birefringent filter has the advantage over a grating of a small insertion loss. The fiber used in these experiments was nonpolarization preserving, and hence the output from the fiber was, in general, elliptically polarized. To obtain a low insertion loss for the birefringent filter requires a linearly polarized beam incident upon the filter. This was achieved by using two quartz quarter-wave plates, which could be rotated independently. With this arrangement any elliptical polarization can be converted to a given linear polarization. It was found that as the laser was tuned it was necessary to make small adjustments of the quarter-wave plates to maintain maximum output. A polarization-maintaining fiber would remove the need for this readjustment of polarization.

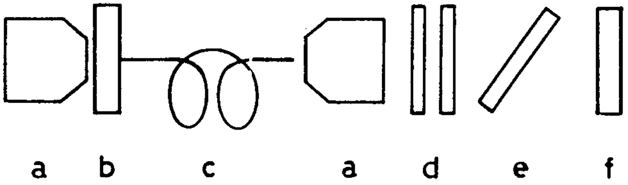

Fig. 1. Schematic diagram of the fiber-laser cavity: a's, microscope objectives; b, high reflector; c, doped fiber; d, quarter-wave plates; e, birefringent filter; f, output coupler.

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The first report of continuous-wave operation on the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition in a glass host was made recently.[6] Here we report the first observation to our knowledge of tunable operation on this transition. Unlike the ${}^4F_{3/2}$–${}^4I_{11/2}$ transition, which has four-level lasing behavior, the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition involves a significant population in the lower laser level. Lasing on the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition can therefore be suppressed as a result of reabsorption loss if too long a fiber is used. Careful optimization of the fiber length was not attempted, but a 1-m length was found to give a reasonable compromise between the need to ensure essentially complete pump absorption and the need to minimize reabsorption loss.

The input mirror was chosen to have a reflectivity of approximately 99.5% at 900 nm and 15% at 1.08 μm, which gave sufficient discrimination to suppress lasing on the ${}^4F_{3/2}$–${}^4I_{11/2}$ transition. The output coupler had a reflectivity of approximately 70% at 900 nm. In the absence of a tuning element in the cavity it was found that the laser would operate at either 906 or 935 nm, corresponding to the two peaks in the fluorescence curve (Fig. 2). It was found that changes in the objective-to-fiber-end distance of approximately 5 μm were sufficient to cause the wavelength to jump between these values. A possible explanation for this behavior is that the different mode size in the fiber for these two wavelengths requires different mode-matching conditions and hence a different location of the microscope objective. However, when a two-plate birefringent filter was placed in the cavity, continuous tuning from 900 to 945 nm was achieved, as shown in Fig. 2, and the free-running linewidth was reduced from 1 to 0.06 nm, FWHM. At threshold the absorbed pump power was 8 mW (unchanged from the value without the birefringent filter), and the output power was 3.2 mW at the peak of the tuning curve for an absorbed pump power of 53 mW.

For operation on the ${}^4F_{3/2}$–${}^4J_{11/2}$ transition the input mirror was chosen to have a reflectivity of approximately 98.5% at 1.08 μm, and the output coupler a reflectivity of approximately 70%. In this case the population of the lower laser level was small, thus giving negligible reabsorption. A fiber length of 2 m was chosen so that the pump power was totally absorbed. The choice of mirrors together with the longer length of the fiber provided sufficient discrimination to suppress operation on the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition.

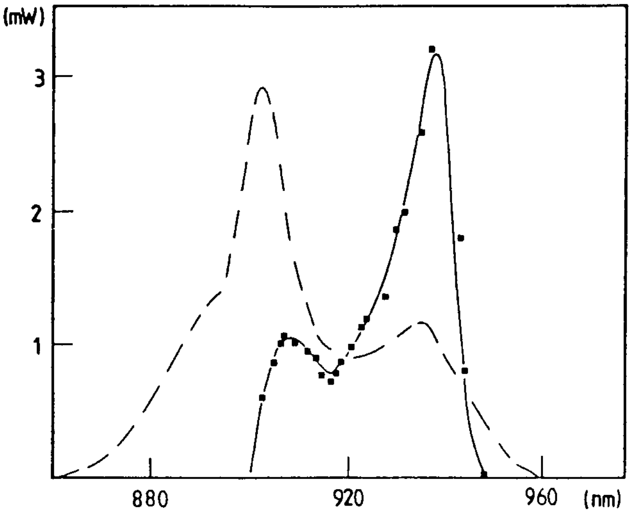

Fig. 2. Photoluminescence spectrum (dotted line) and laser output power variation with wavelength (solid line) for the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition. (The photoluminescence spectrum is not corrected for material reabsorption.)

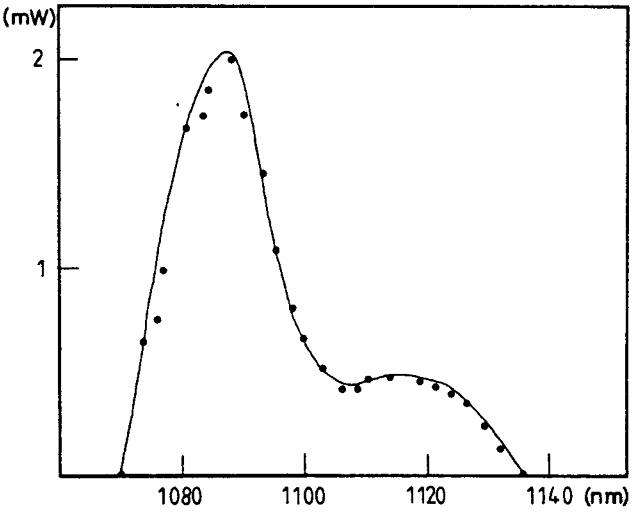

Fig. 3. Laser output power variation with wavelength for the ${}^4F_{3/2}$–${}^4I_{11/2}$ transition.

When the laser was free running without tuning elements it operated at 1.088 μm with a linewidth of 4 nm. Unlike in the case of the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition, the operating wavelength did not change with adjustment of the focusing of the microscope objective. There was no noticeable drop in the output power when the birefringent filter was placed inside the cavity.

The tuning range obtained with the birefringent filter was from 1.07 to 1.135 μm (Fig. 3). The laser linewidth was measured to be 0.1 nm (FWHM). At the peak of the tuning curve the output was 2 mW for 35 mW of absorbed pump power with an absorbed pump power threshold of 12 mW.

The tuning range of 65 nm achieved with this birefringent filter was limited by the inadequate suppression of satellite transmission peaks of the filter, so that at the extreme of the tuning range the wavelength would jump back to near the line center. Tuning on the ${}^4F_{3/2}$–${}^4I_{11/2}$ transition in a fiber laser was previously observed by using a grating,[2] which permitted a slightly greater range, 70 nm, since it was not limited by wavelength hopping. On the other hand, the birefringent filter has permitted more than a 1-order-of-magnitude increase in efficiency over the grating as a result of its much lower insertion loss. An improved tuning range, while maintaining the efficiency, should be possible with a birefringent filter designed specifically for the fiber laser, which, having a higher gain than typical cw dye lasers, needs a better suppression of satellite filter transmission peaks.

A measurement of fluorescence intensity from the fiber on the $^4F_{3/2}$–$^4I_{13/2}$ transition, at around 1.3 μm, indicated a branching ratio similar to that found in other Nd-doped materials. The possibility of laser action on this transition appeared feasible and was looked for.

To minimize the resonator loss the mirrors (~99% reflectivity at ~1.3 μm) were butted to each end of the fiber. Also, to improve the overlap of the fiber mode with the core, a fiber of longer cutoff wavelength (~1.3 μm) was used, having been pulled from the same preform as the fiber used in the earlier experiments. Based on the performance at 0.9 and 1.08 μm, sufficient inversion should have been available to permit oscillation at ~1.3 μm. This was not observed. The likely explanation for this is excited-state absorption, with the $^4F_{3/2}$–$^4G_{7/2}$ transition as the most probable assignment. To check whether absorption was present in the fiber at ~1.3 μm, a probe beam from a miniature diode-pumped Nd:YAG laser operating on the $^4F_{3/2}$–$^4I_{13/2}$ transition[7] was used. The transmission of this probe beam (which was at either 1.32 or 1.34 μm) through the fiber was monitored while the 590-nm pump beam was modulated by a mechanical chopper. Absorption at both probe wavelengths was observed; it was stronger at 1.32 μm where ~40% absorption for an absorbed pump power of 20 mW was observed, while at 1.34 μm ~12% absorption was observed under similar conditions. The absence of lasing therefore appears to be due to excited-state absorption.

We have demonstrated tuning of a Nd^{3+}-doped fiber laser on two transitions, using a birefringent filter as the tuning element. This is the first report to our knowledge of wavelength tuning on the $^4F_{3/2}$–$^4I_{9/2}$ transition. Compared with a grating-tuned fiber laser,[2] the birefringent filter has permitted an increase of efficiency by more than an order of magnitude. The efficiency under conditions of narrow-line operation is comparable with that obtained from dye lasers, vibronic lasers, and color-center lasers, despite the inhomogeneous broadening of the laser transition. It is therefore anticipated that further narrowing, to single-frequency operation, should not entail any significant reduction in efficiency. Given the possibility of incorporating other dopants into the fiber, thus extending the wavelength range, we believe that fiber lasers can offer convenient and attractive alternatives to existing cw near-infrared lasers.

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