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Tunable Single-Mode Fiber Lasers

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Abstract—**Tunable laser action has been obtained in Nd^{3+}- and Er^{3+}-doped single-mode fiber lasers. In the case of the Nd^{3+}-doped fiber, an extensive tuning range of 80 nm has been achieved. Tunable CW lasing also has been observed for the first time in an Er^{3+}-doped fiber laser, which has an overall tuning range of 25 nm in the region of $\lambda = 1.54$ μm.**

I. INTRODUCTION

A CLASS OF active fiber devices compatible with single-mode fiber systems is highly desirable to supplement the hybrid semiconductor-diode/optical-fiber technologies currently in use. As a first step towards this goal, we have recently demonstrated lasing action in rare-earth-doped silica single-mode fibers [1]–[3]. Using a new manufacturing process [4], it it possible to fabricate single-mode fibers with dopant concentrations up to 900 ppm, while maintaining the low-losses which are characteristic of telecommunications fibers. The fibers are fully compatible with existing fiber devices such as fused couplers [5], polarizers [6], filters [7], and phase modulators [8], and consequently, it is possible to envision a new all-fiber laser technology.

Multimode rare-earth doped fiber lasers have been reported by several authors [9], [10]. Single-mode fiber lasers (SMFL) possess a number of advantages over these devices. By virtue of their small cores, very low thresholds and high gains can be achieved. Since the typical fiber diameter is about 100 μm, thermal effects which plague glass lasers are minimal. The fabrication process is economical in dopant, since a typical device uses only 0.1 μg of rare-earth oxide. Devices can be packaged compactly—a coiled 1-m long laser readily fits into a 1-cm^3 enclosure.

Silica, the laser medium, has good power handling characteristics; moreover, it broadens the rare-earth transitions, enabling tunable lasers and broad-band amplifiers to be constructed. Despite the broad linewidths obtained, threshold power is still low due to the small core size of the fibers used in these experiments. Thresholds as low as 100 μW have been obtained using a semiconductor diode laser as a pump source [1] and, with near optimum output coupling, it is possible to obtain a slope efficiency of 30 percent [11].

To date we have obtained laser action in two of the rare-earth dopants (Nd^{3+} and Er^{3+}) incorporated into silica single-mode fibers [1], [3]. Nd^{3+}-doped fiber lasers operate on the familiar ${}^4F_{3/2}$–${}^4I_{11/2}$ transition usually associated with 1.059 μm emission in bulk glass lasers. However, in silica the maximum of the gain profile is at 1.088 μm with a FWHM of approximately 50 nm [10]. The fluorescent lifetime has been measured to be 470 μs ± 20 μs [12].

Lasing in Er^{3+}-doped fibers also has been obtained on the ${}^4I_{13/2}$–${}^4I_{15/2}$ (groundstate) transition [2], [3]. The fluorescence curve consists of two peaks at 1.534 and 1.549 μm and the fluorescent lifetime has been measured to be 14.0 ± 0.5 ms. The peak gain is at 1.534 μm where erbium operates as a three-level laser [13]. To our knowledge this work represents the lowest threshold and only room temperature CW three-level glass laser yet reported. We report here experiments on the tunability of both Nd^{3+}- and Er^{3+}-doped fiber lasers and show that both are widely tunable over their gain curves.

II. THEORY

To understand the low-threshold advantage of a SMFL, we will estimate the lasing threshold for an Er^{3+}-doped fiber laser in an end-pumped configuration. If we assume that Er^{3+} is an ideal 3-level laser system, it requires at least half the Er^{3+} ions to be pumped into the excited state before laser action can occur. The high pump power needed and the associated thermal problems make room-temperature continuous operation of 3-level laser systems very difficult. As we shall see, this is not the case for a SMFL.

Using the 3-level model shown in Fig. 1, we obtain the usual rate equations

$$\frac{dN_1}{dt} = -R_{13}N_1 + \frac{N_2}{\tau_{21}} + (N_2 - N_1)\,W_2 \tag{1}$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - (N_2 - N_1)\,W_2 \tag{2}$$

$$\frac{dN_3}{dt} = R_{13}N_1 - \frac{N_3}{\tau_{32}} \tag{3}$$

where

N_i	total population in level i ($i = 1, 2, 3$)
$R_{13}N_1$	pump rate from level 1 to 3,
τ_{ij}	inter-level lifetimes, where i, j denote the two levels,
$(N_2 - N_1)\,W_2$	stimulated emission rate.

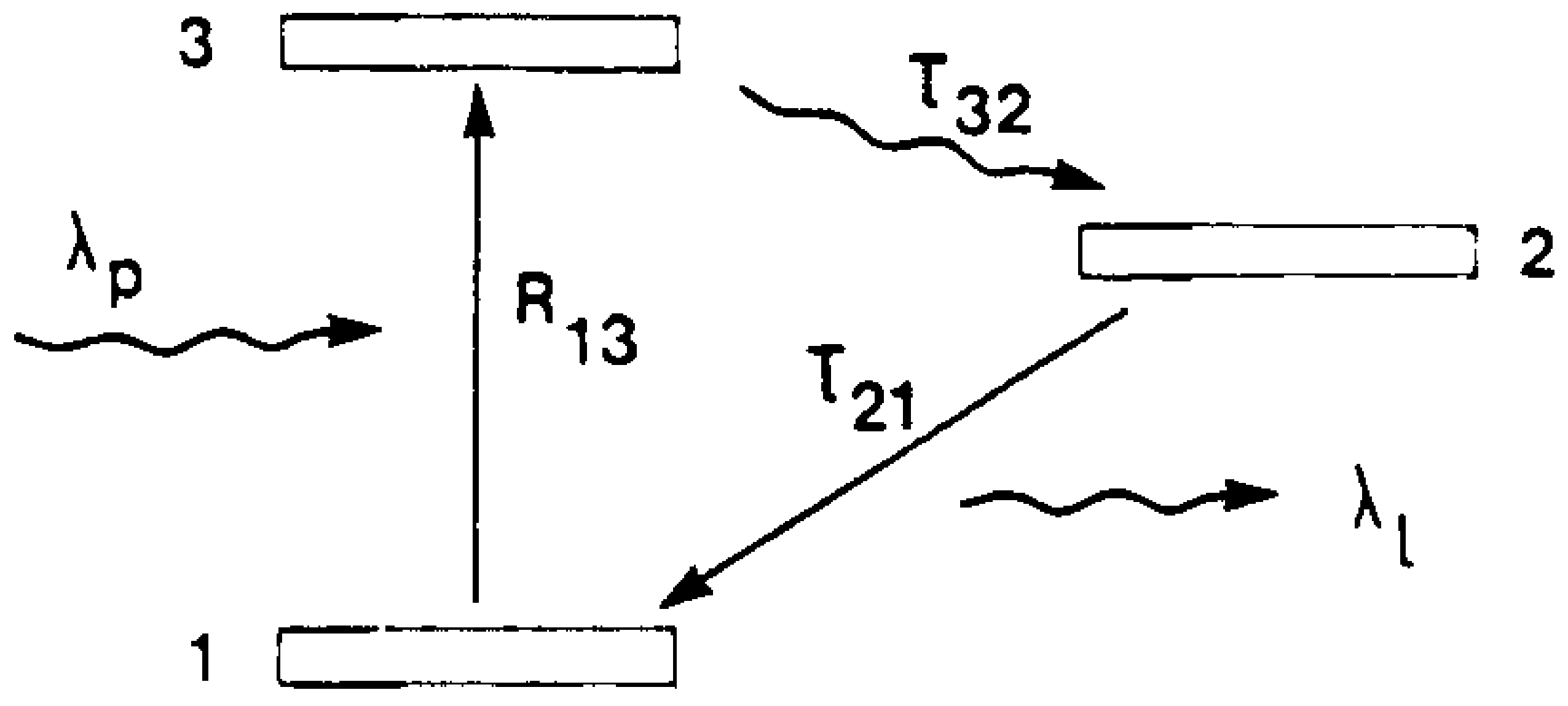

Fig. 1. Energy level diagram for an ideal 3-level laser.

In the steady-state $d/dt = 0$, we have

$$\frac{N_3}{\tau_{32}} = R_{13}N_1. \tag{4}$$

Since we are dealing with an ideal three-level system where the nonradiative lifetimes $\tau_{32} << \tau_{21}$, we can assume that $N_2 >> N_3$ and obtain

$$N_2 = \frac{R_{13}N_1}{1/\tau_{21} + W_2}. \tag{5}$$

When a fiber of cross-sectional area A is end-pumped by a laser with frequency ν_p, the number of ions excited per second at any point along the length of the fiber may be expressed as

$$R_{13}N_1 = \frac{I_p\sigma_A}{h\nu_p} N_1 \tag{6}$$

where σ_A is the absorption cross section at ν_p and I_p is the local pump intensity.

Since N_3 is negligible, $N_1 = N_T - N_2$, where N_T is the total number of ions in an incremental volume. Thus, from (5) and (6), the inversion $N_2 - N_1$ is given by

$$N_2 - N_1 = \frac{I_p\sigma_A/h\nu - 1/\tau_{21} - W_{21}}{I_p\sigma_A/h\nu + 1/\tau_{21} + W_{21}} N_T. \tag{7}$$

If we assume that $W_{21} << 1/\tau_{21}$, then in order to achieve an inversion at any point in the fiber we require

$$I_p > \frac{h\nu_p}{\sigma_A \tau_{21}}. \tag{8}$$

Using typical values for Er^{3+} ions in silica glass, ($\nu_p = 5.8 \times 10^{14}$ s^{-1}, $\sigma_A = 2 \times 10^{-21}$ cm^2, and τ_{21} = 14 ms, and for the fiber used in this experiment), we calculate a threshold pump power of only 15 mW. This figure can be improved on by decreasing intracavity losses [3]. It is therefore possible to obtain continuous lasing with extremely low input powers and no auxiliary cooling requirement, unlike conventional 3-level lasers which are operated in a pulsed mode and which require a pump power of several kilowatts. Furthermore, it should be possible to significantly exceed threshold by injecting into the fiber several tens of milliwatts of pump light from a semiconductor diode laser source and thus obtain high gain levels. Moreover, wide tuning of the laser oscillation wavelength over a large portion of the gain curve can be achieved.

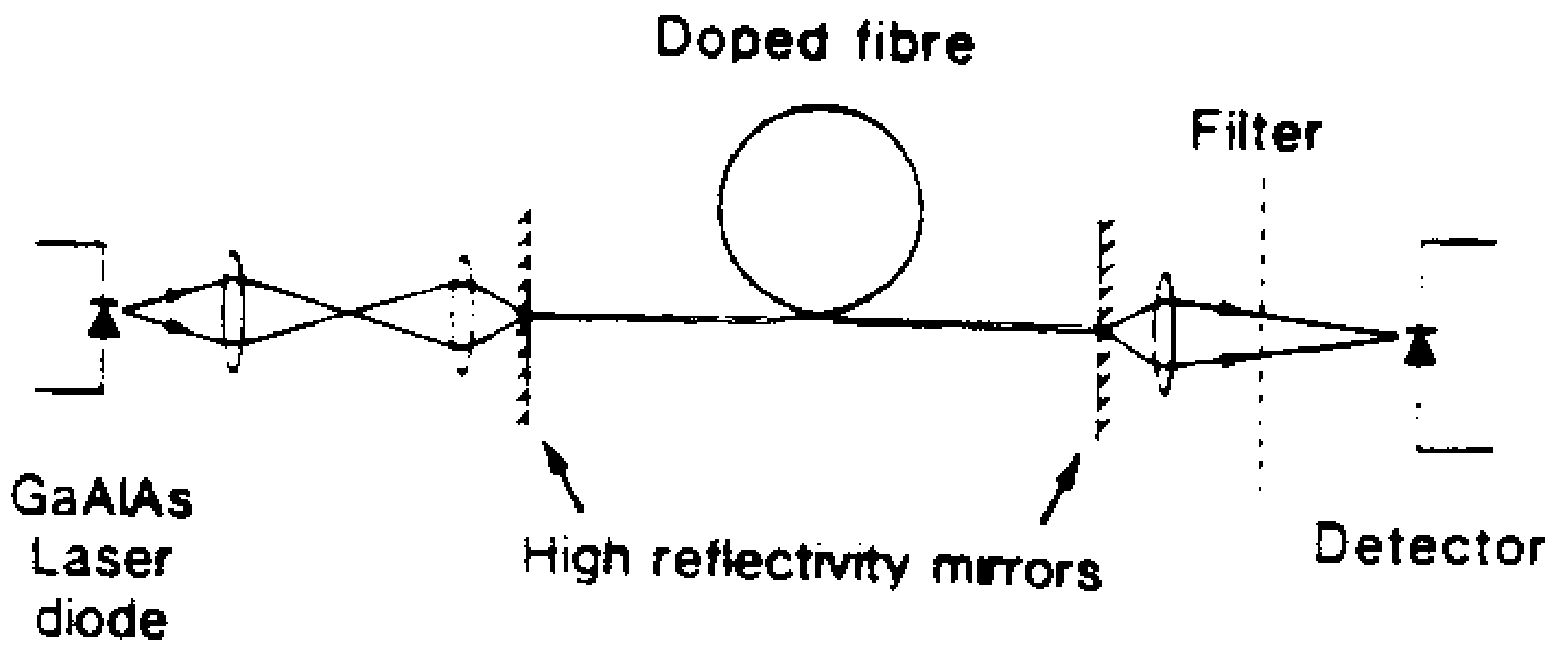

Fig. 2. Experimental configuration of a semiconductor laser pumped single-mode fiber laser.

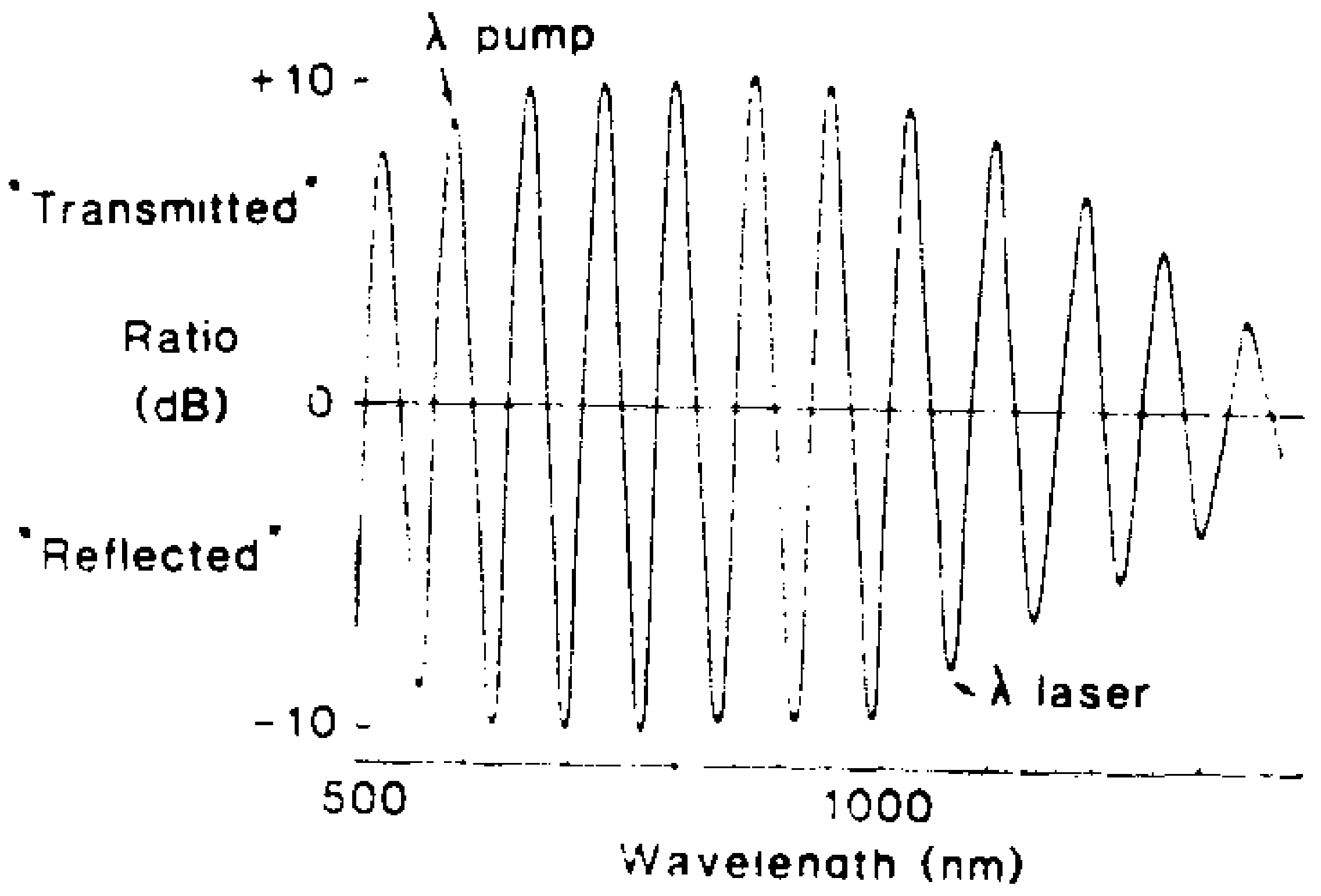

Fig. 3. Wavelength coupling characteristic of ring resonator fiber coupler.

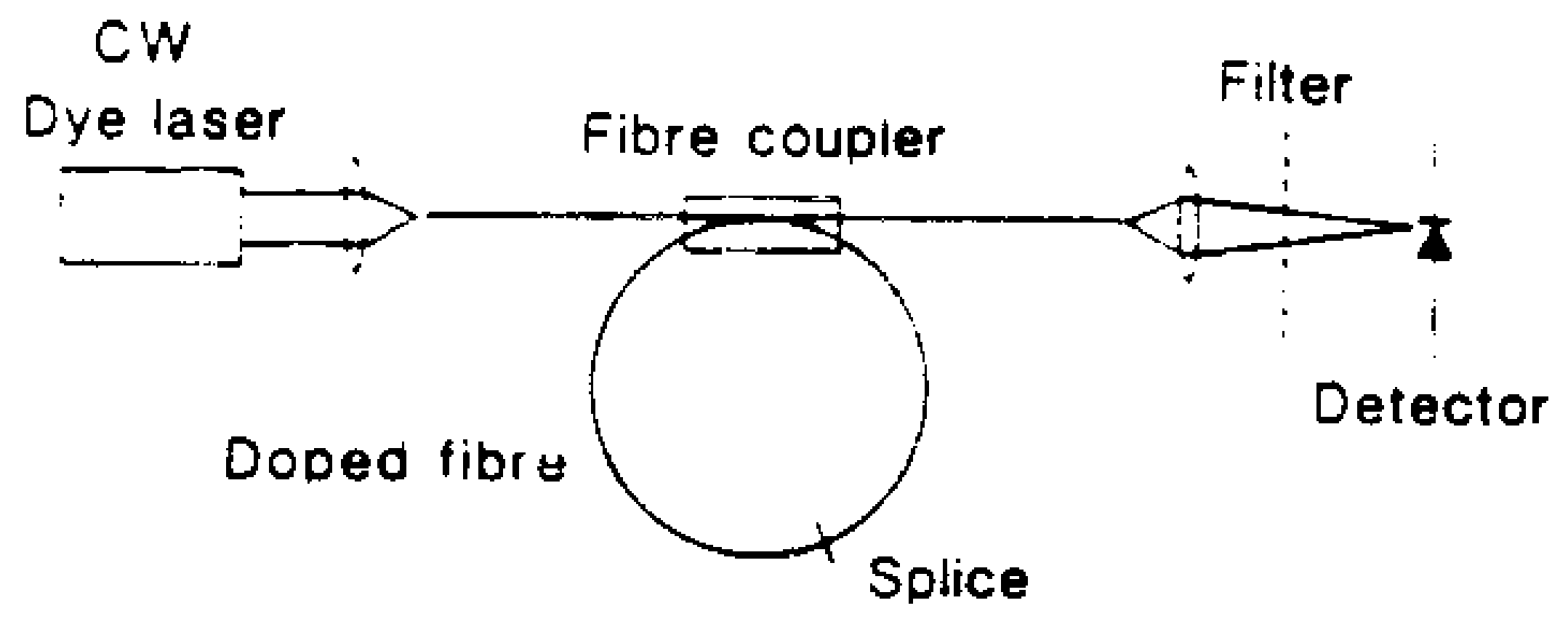

Fig. 4. Experimental configuration of dye laser pumped ring cavity single-mode fiber laser.

In Nd^{3+}-doped fiber, even lower threshold values can be expected, since this is a four-level laser system. Population inversion can therefore be obtained by pumping far less than half the ions to an excited state.

This is demonstrated by the very low threshold (100 μW) obtainable in a Nd^{3+}-doped-silica SMFL pumped with a GaAlAs laser diode [1]. As shown in Fig. 2, the fiber ends were simply cleaved and butted to dielectric mirrors having high reflectivity (>99 percent) at the lasing wavelength of 1.088 μm while giving good transmission at the pump wavelength of 820 nm.

In another experiment that obviates the requirement for high-quality dielectric mirrors, an all-fiber ring laser was constructed [1]. A four-port single-mode fused tapered coupler with the spectral characteristic shown in Fig. 3 was fabricated from Nd^{3+}-doped fiber. Two of the fibers were spliced together to form a ring cavity with moderate finesse at the lasing wavelength and good input coupling (>80 percent) at the pump wavelength of 595 nm (Fig. 4). The importance of lasers of this configuration is that the output power is guided by a fiber, permitting direct splicing to other fiber systems.

III. EXPERIMENTAL

A. Tuned Nd^{3+}-Doped Fiber Lasers

The experimental configuration is shown in Fig. 5. The pump source used was a Spectra-Physics 2020 argon-ion laser capable of delivering approximately 3 W at λ =

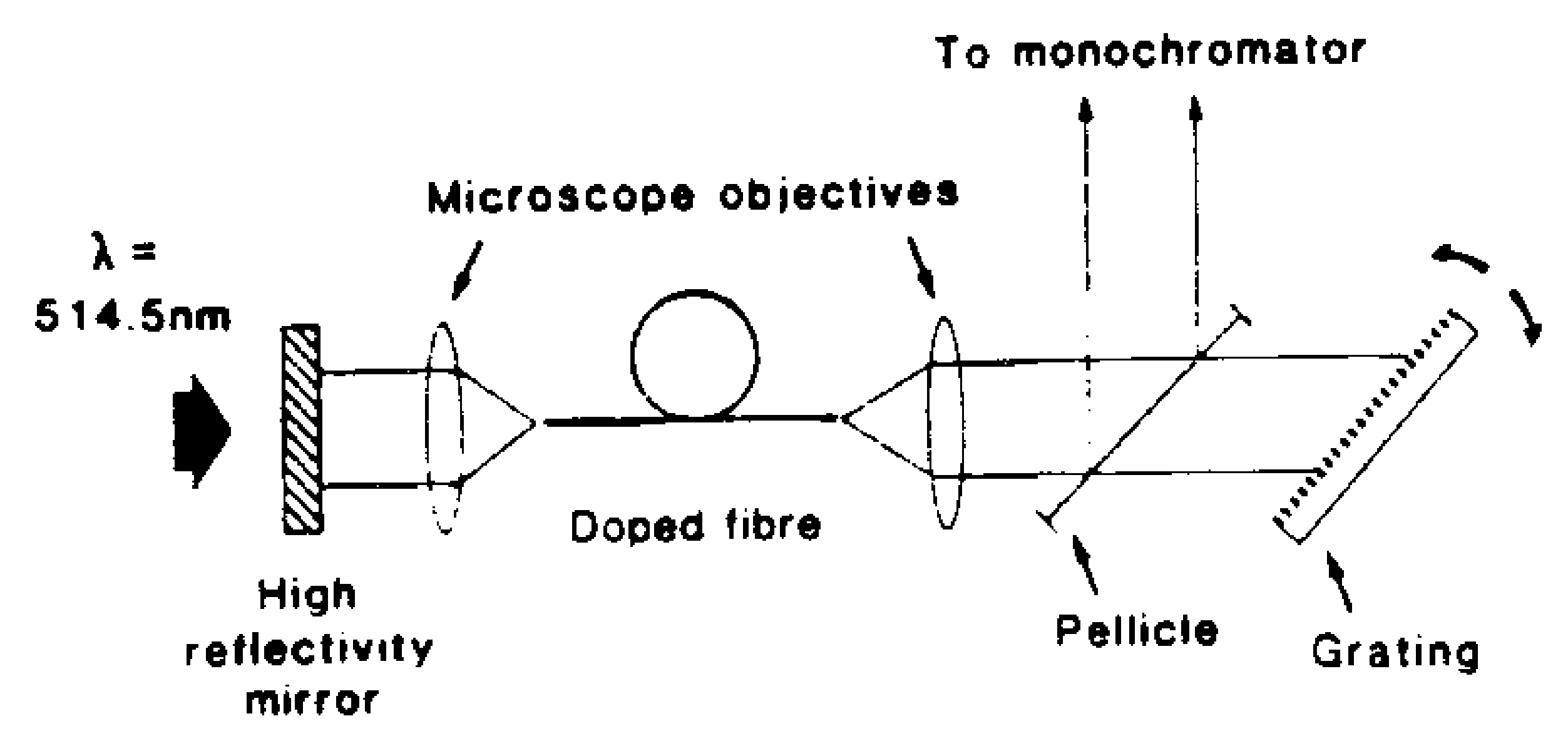

Fig. 5. Experimental configuration of tunable Nd^{3+}-doped single-mode fiber laser.

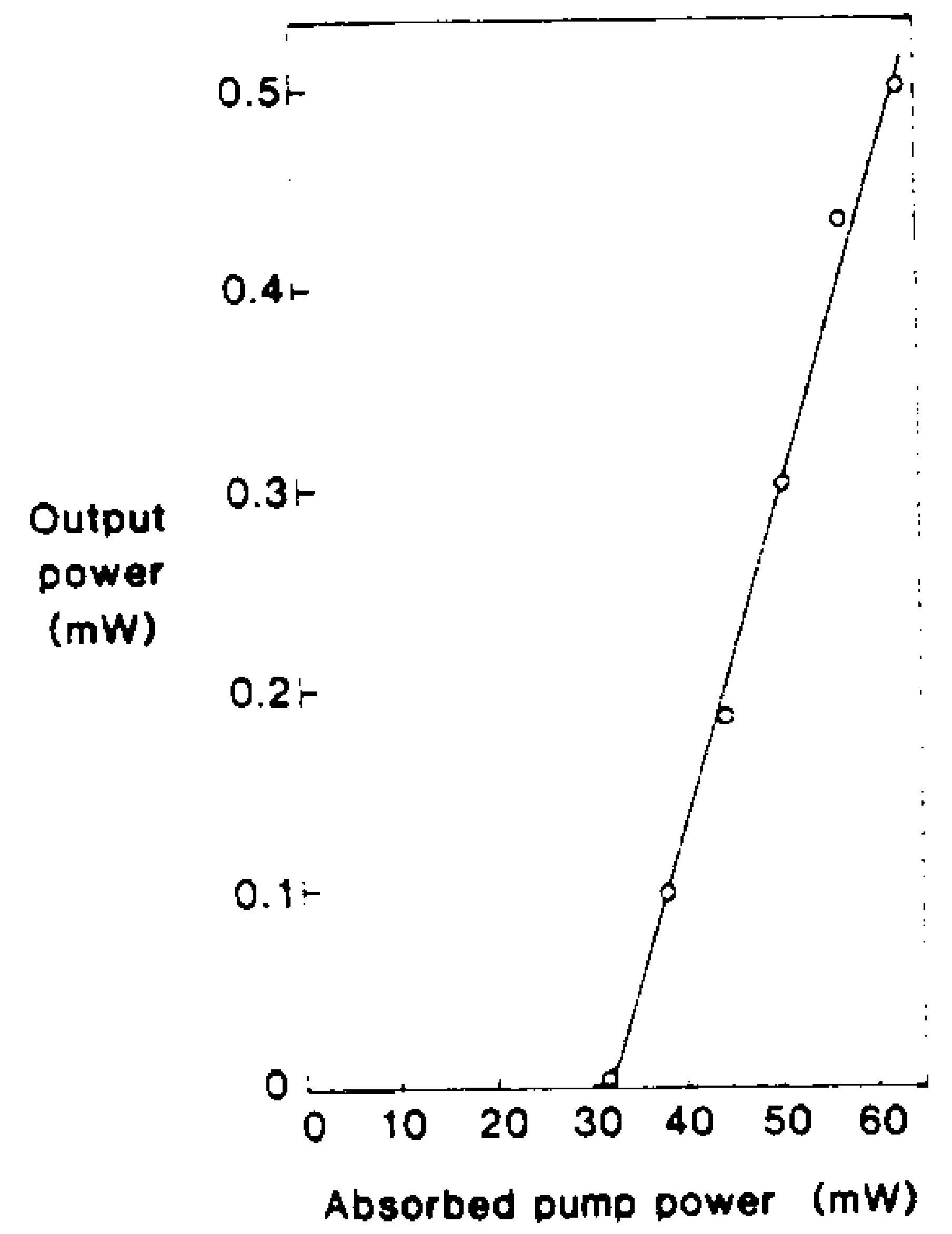

Fig. 6. Lasing characteristic of tunable Nd^{3+}-doped single-mode fiber laser.

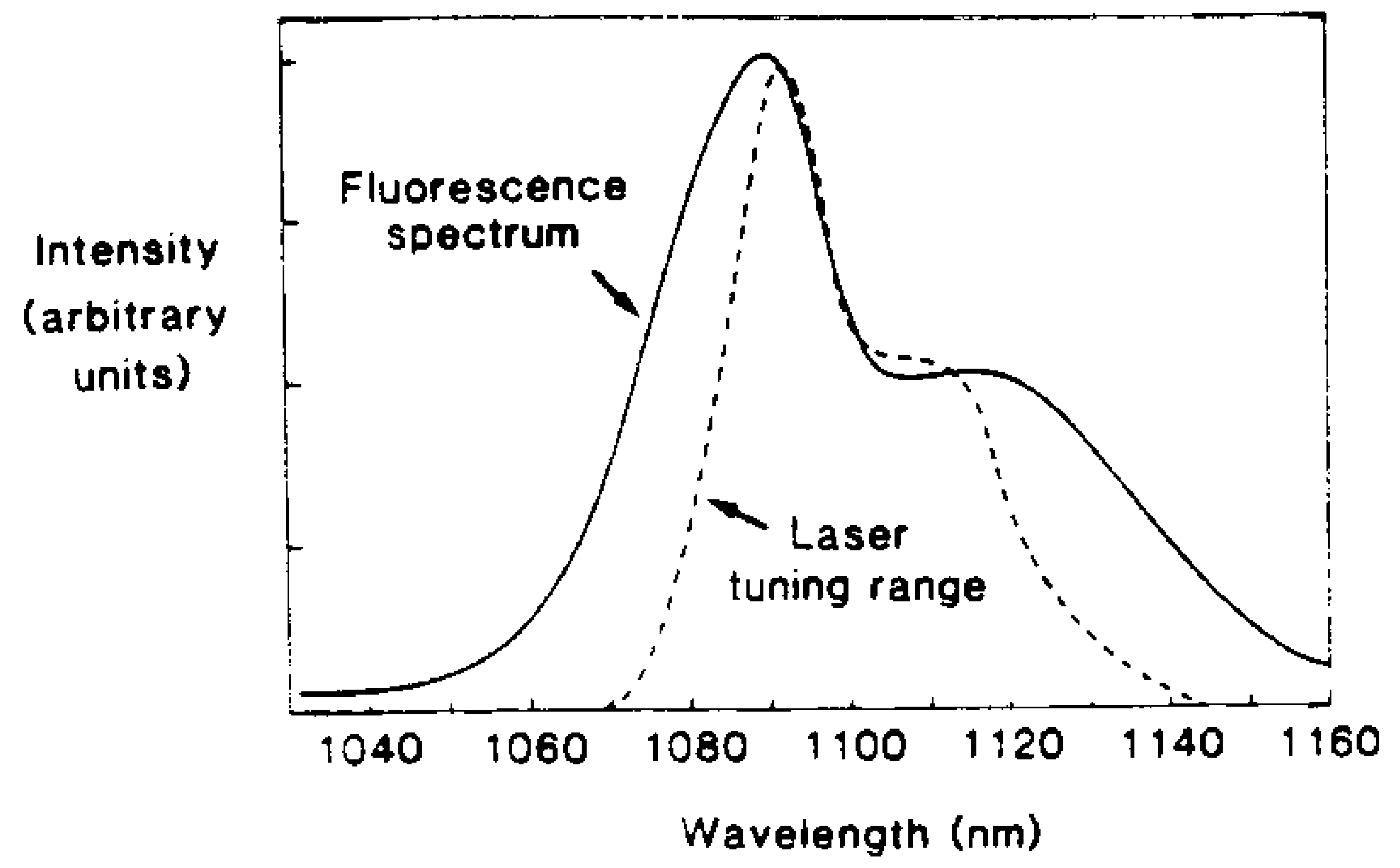

Fig. 7. Laser tuning range and fluorescence spectrum of Nd^{3+}-doped single-mode fiber laser.

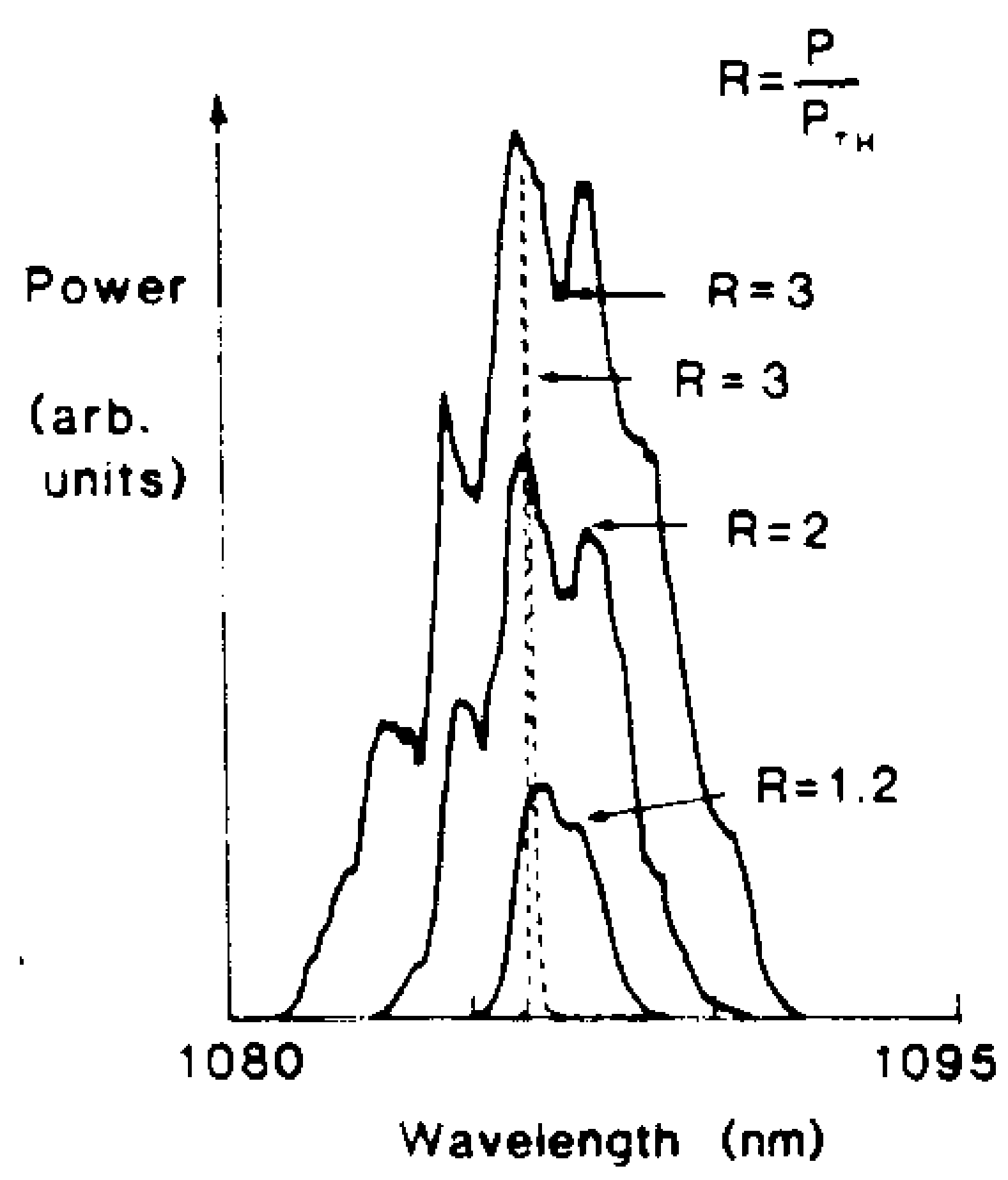

Fig. 8. Spectral bandwidth of tuned and untuned Nd^{3+}-doped single-mode fiber laser emission.

514.5 nm, the pump wavelength used in this experiment. The gain medium consisted of a 5 m length of Nd^{3+}-doped single-mode fiber which had an unsaturated absorption of 10 dB/m at $\lambda = 514.5$ nm [4]. The exceedingly low intrinsic loss of the fiber (< 10 dB/km at $\lambda = 1.088$ μm), allowed the use of long lengths of fiber, up to 300 m in one instance. The input mirror was a conventional, plane, high-reflectivity laser mirror with >99-percent reflectivity at the lasing wavelength and approximately 80-percent transmission for the pump beam. Light was coupled into the cleaved fiber end with an efficiency of ~20 percent using an intracavity microscope objective (×10, 0.25 NA). The fiber had a cutoff wavelength of 950 nm and a numerical aperture of 0.2. Output from the fiber was collimated onto a diffraction grating (600 lines/mm, blazed at $\lambda = 1$ μm) in order to provide wavelength-selective feedback and thus spectral narrowing. Tuning was accomplished by changing the angle of the diffraction grating, which was mounted on a sine-bar-driven turntable. An intracavity pellicle was used as the output coupler.

The lasing characteristic is shown in Fig. 6. It was possible to vary the output power and lasing threshold by altering the angle of the pellicle, but the pellicle reflectivity was too low to achieve optimum output coupling. In this rather lossy cavity configuration, laser threshold was found to occur at an absorbed pump power in the fiber of 30 mW, giving a slope efficiency of 1.7 percent. Laser threshold could be reduced by butt coupling the fiber end to the input mirror, thus reducing the intracavity losses incurred by using the microscope objectives, and submilliwatt thresholds have been achieved using this technique [1].

The laser tuning curve is shown in Fig. 7. The pump power used was 125 mW, corresponding to an absorbed pump power in the fiber of only 51 mW. The fluorescence spectrum of Nd^{3+} ions in silica is shown for comparison. It can be seen that a tuning range of 80 nm is obtained, corresponding to most of the available gain profile. To our knowledge this is the most extensive tuning range obtained in a Nd : glass laser.

The spectral content of the tuned and line-narrowed SMFL was measured using a double monochromator having a resolution of 0.1 nm at $\lambda = 1.08$ μm. As a comparison, the spectrum of the untuned laser also was measured by replacing the grating with a high-reflectivity laser mirror. Laser threshold and output power in this latter configuration were similar to that of the tuned laser operating at the peak of the gain curve. The spectrum of the untuned laser was measured at various pump powers above threshold and the results are shown in Fig. 8. It can be seen that the bandwidth broadens to a FWHM of approximately 5 nm at three times above threshold. Note that the periodic modulation of the spectrum at approximately 2-nm intervals is due to an intracavity Fabry–Perot etalon formed between the microscope objective and the fiber. This effect could be eliminated by butting the fiber against the input mirror.

The superimposed narrowband spectrum in Fig. 8 is that

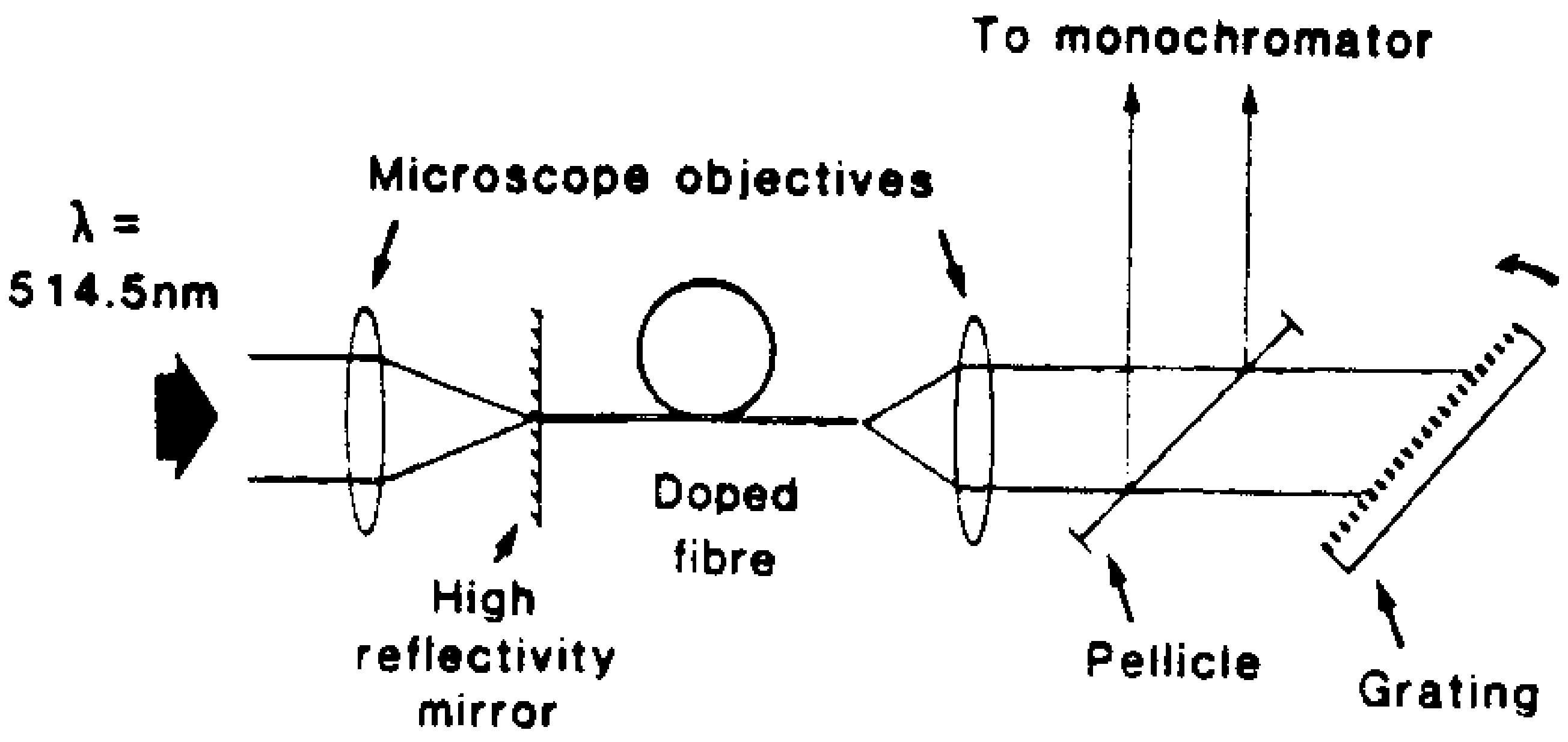

Fig. 9. Experimental configuration of tunable Er^{3+}-doped single-mode fiber laser.

of the tuned laser when operated near the gain maximum at three times threshold pump power (not to scale). The FWHM of the spectral bandwidth in this configuration was found to be 0.25 nm, and since the output power was similar in both narrowed and unnarrowed configurations, this represents a 20-fold increase in spectral brightness. Calculation shows that the 0.25-nm linewidth was limited by the spotsize on the intracavity grating.

Tunable laser emission also has been obtained on the 3-level $^4F_{3/2}$–$^4I_{9/2}$ transition of Nd^{3+} ions in the same fiber. In initial experiments, a tuning range of 899–951 nm has been obtained using an experimental configuration similar to Fig. 5.

B. Tuned Er^{3+}-Doped Fiber Lasers

A similar experimental arrangement was used to tune the output of the Er^{3+}-doped fiber laser (Fig. 9). In this case however, it was necessary to minimize the excessive losses caused by chromatic abberation in the uncorrected microscope objectives and so the fiber was cleaved and butted to the input mirror. A 90 cm length of Er^{3+}-doped single-mode fiber with an unsaturated absorption of 10 dB/m at λ = 514.5 nm was used as the gain medium. Cutoff wavelength of this fiber was 1 μm, and the NA was 0.22. The input mirror had 82-percent reflectivity at λ = 1.54 μm and 77-percent transmission at λ = 514.5 nm. A holographic diffraction grating having 600 lines/mm and blazed at λ = 1.6 μm was used to provide wavelength-selective feedback. Once again, a pellicle was used as the output coupler.

The lasing characteristic is shown in Fig. 10. Despite the losses incurred by the remaining microscope objective and also the three-level nature of the transition involved, laser threshold and output power were similar to that of the Nd^{3+}-doped fiber laser. Once again, the pellicle did not provide optimum output coupling, and a slope efficiency of 0.6 percent was obtained. The characteristic does not take into account laser emission lost through the partially transparent input mirror. CW operation was easily achieved with a threshold which is several orders of magnitude less than that of previously reported three-level lasers.

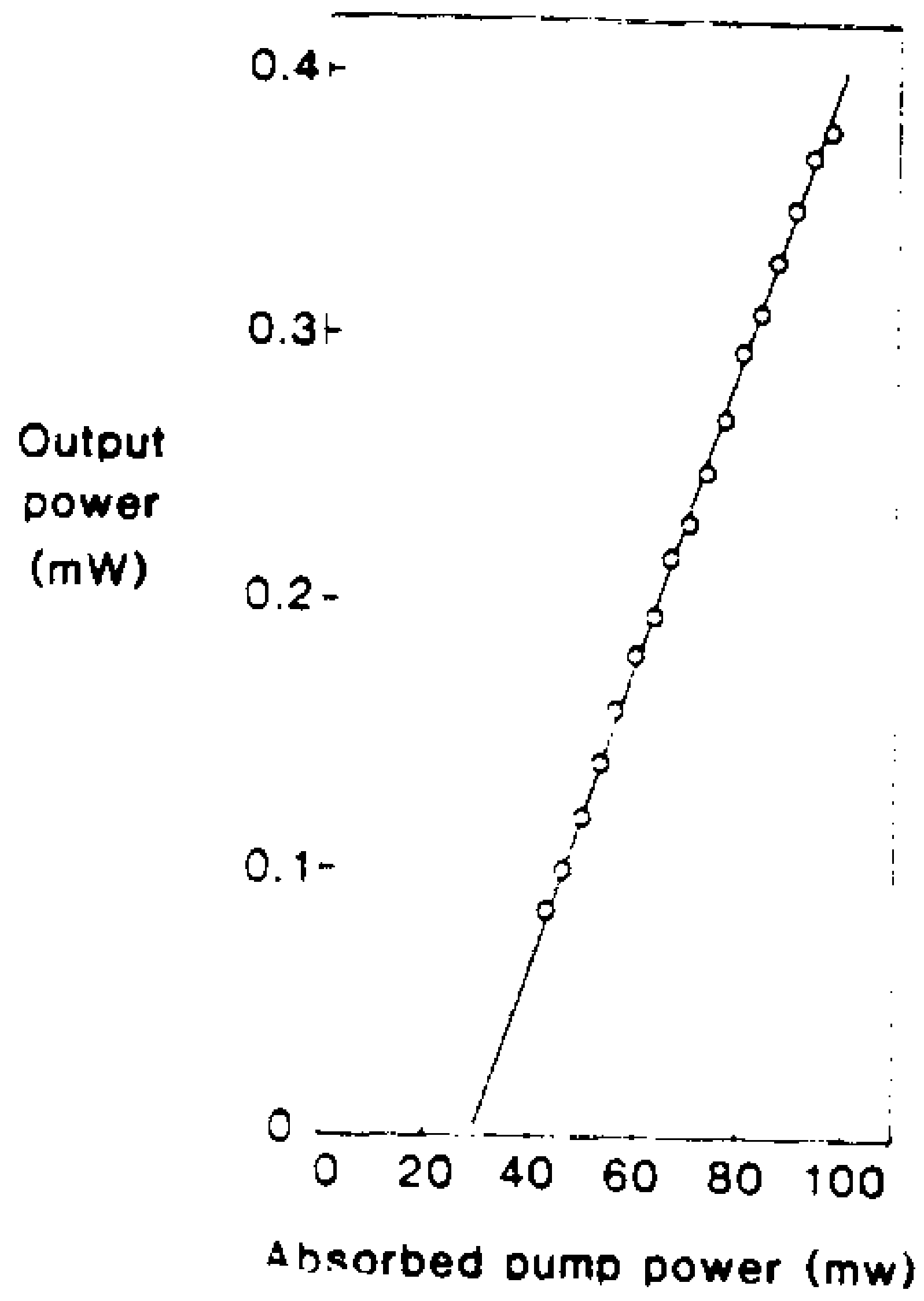

Fig. 10. Lasing characteristic of tunable Er^{3+}-doped single-mode fiber laser.

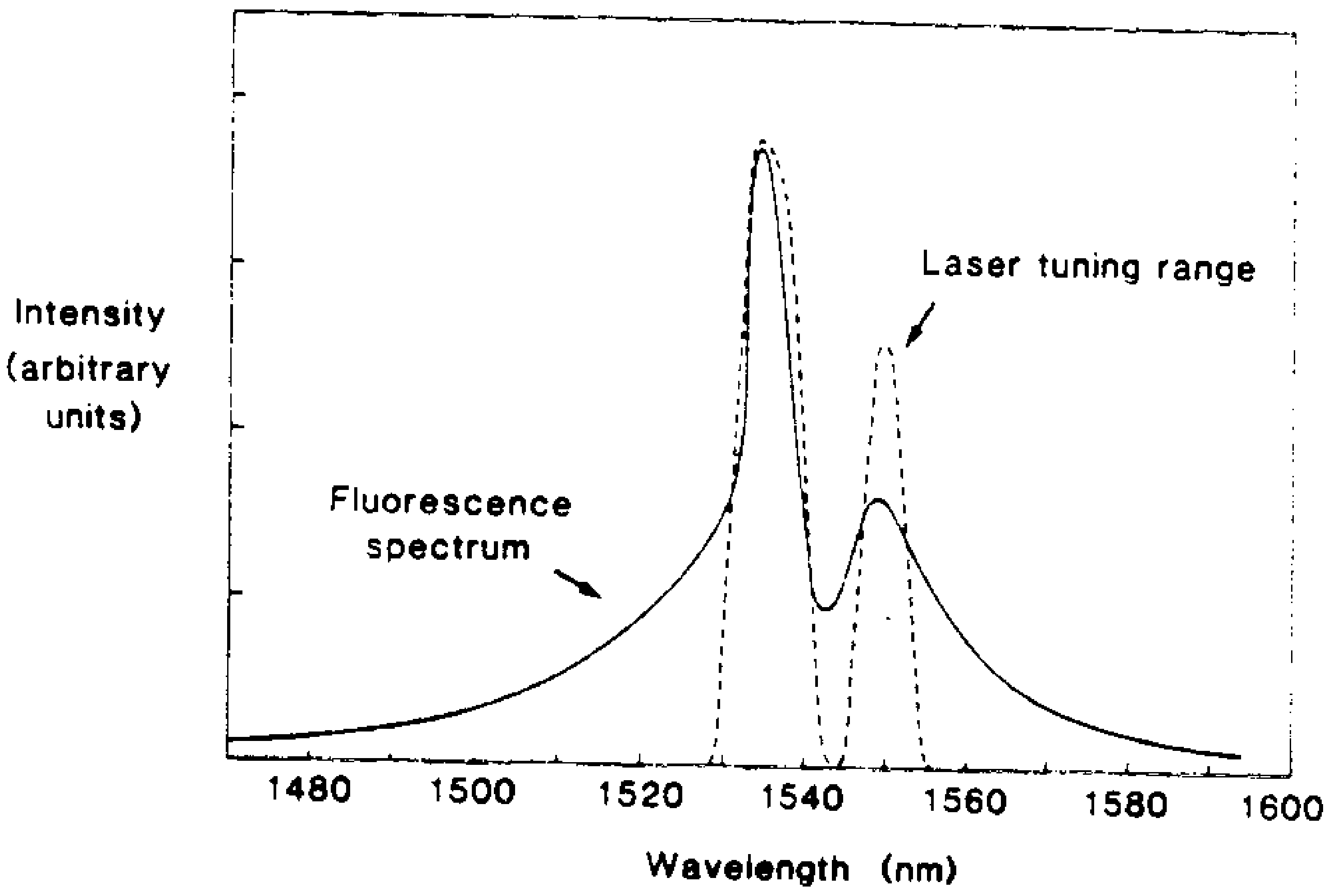

Fig. 11. Laser tuning range and fluorescence spectrum of Er^{3+}-doped single-mode fiber laser.

The tuning curve of the laser is shown in Fig. 11. This curve was taken at an absorbed pump power of 90 mW, three times that of threshold. At this pump level, it was not possible to achieve continuous tuning over the range concerned. Nevertheless, two broad tuning bands of approximately 14 and 11 nm, respectively, were obtained. Thus, the lasing output could be tuned over most of the important "third window" for optical communications.

IV. Conclusion

Tunable laser action has been observed in Nd^{3+}- and Er^{3+}-doped single-mode fiber lasers. An extensive tuning range of 80 nm has been obtained with the Nd^{3+}-doped fiber. Tunable continuous operation of a three-level Er^{3+} laser has been obtained for the first time with a remarkably low threshold. In this case, an overall tuning range of 25 nm was obtained around λ = 1.54 μm. It is anticipated that these single-mode fiber lasers will be useful in making dispersion and tunable backscatter measurements in optical fibers for telecommunications.

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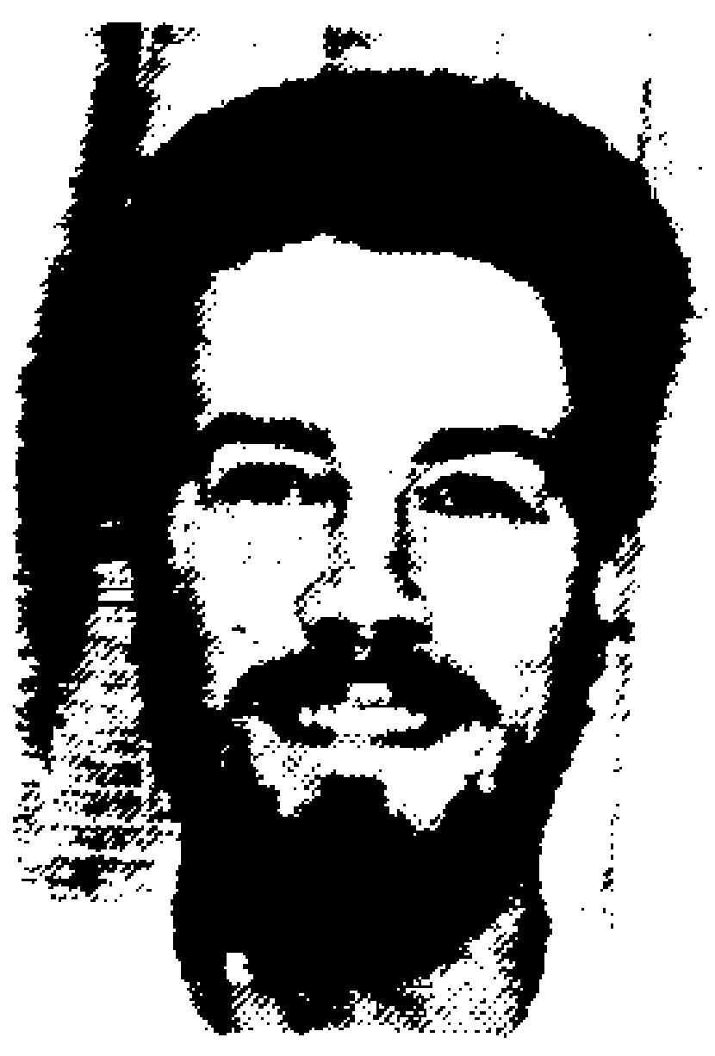

Simon B. Poole was born in Watford, England, in 1958. He received the B.Sc. in electrical and electronic engineering from the University of Nottingham in 1979.

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Dr. Payne is an Associate Editor of the JOURNAL OF LIGHTWAVE TECHNOLOGY.