Wavelength Tunability in a Nd-Doped Fiber Laser with an Intracavity Polarizer

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Abstract—When an intracavity polarizer is introduced into a Fabry–Perot Nd-doped fiber laser, wide wavelength tunability is achieved either by rotating the polarizer or by varying the fiber birefringence with an in-line polarization controller. The intracavity polarizer also produces considerable line-narrowing. A model based on birefringence dispersion is proposed.

I. INTRODUCTION

Due to a complex combination of spatial hole burning and some inhomogeneous broadening, Nd-doped fiber lasers with a Fabry–Perot cavity are known to emit fairly broad-band light (= 5 nm) at ≈ 1090 nm, with detailed spectral shapes that depend on many parameters [1]–[4]. Since even ordinary, “nonpolarization-maintaining,” single-mode fibers are generally characterized by an anisotropic index of refraction (due either to stress or to core ellipticity) [5], the fiber laser cavity is birefringent [6]–[8]; thus, the polarization state of the guided light evolves as it propagates along the fiber. In an effort to reduce the number of the degrees of freedom of the cavity, we introduced an intracavity polarizer with the following results: (a) the laser’s linewidth decreased substantially; (b) wide tunability was demonstrated by changing the relative angle between the polarizer and the fiber birefringent axes; and (c) the laser’s spectral coverage was increased more than three fold. While tunability in fiber lasers can be achieved by a few other means [7]–[10], our novel approach is easy and cheap and well suited to laboratory set-ups. In this letter, we describe the device and its performance and also discuss the wavelength selection mechanism involved.

II. EXPERIMENT

The experimental set-up is shown in Fig. 1. A 514 nm argon pump laser was focused through a microscope objective into a cavity composed of two dichroic mirrors (90% reflection at 1090 nm and 90% transmission at 514 nm). To control the fiber birefringence, a portion of the 2.5m Nd-doped fiber (made by York, England; ≈ 500 ppm dopant concentration) was coiled around a polarization controller [5]. The polarization controller was installed near the far end of the fiber, where the pump energy is negligible, to assure that it has no effect on the pump light. While the input end of the fiber was butt-coupled to the front mirror, its output end was imaged on the output coupler, thereby creating enough space for the polarizer and its rotating stage. The IR polarizer had an extinction ratio > 1000 at and around 1090 nm. Since a CCD camera was used to image the output slit of the spectrometer (0.1 nm resolution), all spectral components of the laser emissions were simultaneously recorded (within 1/50 s).

III. RESULTS

Threshold pump power for the laser shown in Fig. 1 was 18 mW, and the results presented here were obtained at a pump power of 29 mW. Typical spectra appear in Fig. 2. The dashed curve shows the spectrum without an intracavity polarizer. With the polarizer installed, continuous coverage of the 1077–1093 nm spectral range was obtained as the polarizer scanned an angle of ≈ 50°, see solid curves of Fig. 2. The fine structure (“wiggles”) in the spectra are due to weak feedback from the intracavity polarizer and imaging lens. Indeed, small displacements and tilts of these components were found to modify this fine structure; however, the 3-dB spectral widths were completely unaffected. Similar tuning was also achieved by varying the overall fiber birefringence using the polarization controller, while at the same time keeping the polarizer in a fixed position. It can be clearly seen that with an intracavity polarizer, the linewidths are about half as large (= 2.5 nm versus ≈ 5 nm) as those obtained without the polarizer. Furthermore, the continuous tuning range of ≈ 15 nm far exceeds the spectral width without the polarizer (= 5 nm). With higher pump power (= 100 mW) we observed tunability over about 42 nm (1078–1120 nm), but the tuning was not continuous; i.e., not every wavelength in the 1078–1120 nm range could be excited. There were, however, settings of the polarization controller which resulted in a much narrower tuning range even for a full 180° rotation of the polarizer. Also, for a given pump power and for a given setting of the polarization controller, lasing was not achieved at all polarizer angles. Each spectral line could always be reproduced by rotating the polarizer by 90° (i.e., the polarizer’s action was found to be periodic with period of π/2). While qualitatively similar, the exact dependence of output wavelength and lineshape on the polarizer angle was found to vary from one doped-fiber to another. It was impossible to obtain tuning with the polarizer in a fiber laser made of a short and straight 32 cm of the same doped-fiber. Finally, well-above threshold none of the above mentioned-phenomena depended on the polarization of the pump beam.

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IV. DISCUSSION

To explain the experimental observations the following model is proposed. The polarizer, located near the output coupler at an angle \( \theta \) with respect to some laboratory frame of reference, fully dictates the state of polarization, \( \mathcal{P}(\theta) \), of the wave at that point (e.g., for a linear polarizer, as used in the experiment, \( \mathcal{P}(\theta) \) represents linear polarization at an angle \( \theta \) to the fixed frame of reference). To be amplified by the doped fiber, the light exiting the polarizer towards the mirror (see Fig. 1) must complete a round trip through the fiber, whose birefringence will substantially modify its state of polarization as it reapproaches the polarizer on its way out. Moreover, due to birefringence chromatic dispersion, different wavelengths will emerge from the round trip with different states of polarization. Since round-trip loss critically depends on the scalar product between the polarization of the incoming wave and that of the polarizer, only those wavelengths will lase for which the loss is low enough to match the available gain. Let \( M(\lambda) \) be the Jones matrix [11] representing the polarization transformation suffered by the wave on its round trip. Assuming, for simplicity, that all other losses are wavelength-independent, lasing will occur at \( \lambda \) if

\[
| \mathcal{P}^\dagger(\theta) \cdot M(\lambda) \cdot \mathcal{P}(\theta) \cdot \exp[G(\lambda)L] \cdot T_{eff} = 1, \tag{1} \]

where \( \dagger \) denotes Hermitian conjugation, \( G(\lambda) \) is the fiber gain at \( \lambda \), \( L \) is the round-trip distance through the amplifying medium, and \( T_{eff} \) represents the assumingly wavelength-independent over-all transmittance of the other optical components in the cavity. It is clear from (1) that wavelength tunability can be achieved either by rotating the polarizer, thereby varying \( \mathcal{P}(\theta) \), or by modifying \( M(\lambda) \) through the adjustment of the polarization controller. Equation (1) also defines the line width, which is evidently narrower than that obtained without the intracavity polarizer. If the gain and loss mechanisms in the doped-fiber are polarization-independent, \( M(\lambda) \) is proportional to a unitary matrix, and it easily follows that if \( \mathcal{P}(\theta) \) satisfies (1), so does the orthogonal polarization \( \mathcal{P}(\theta + 90^\circ) \). Indeed, if \( M(\lambda) \) is represented in a vector basis formed by \( \{ \mathcal{P}(\theta), \mathcal{P}(\theta + 90^\circ) \} \), then it immediately follows from the canonical representation of a unitary matrix [11], that

\[
| \mathcal{P}^\dagger(\theta) \cdot M(\lambda) \cdot \mathcal{P}(\theta) | = |M(\lambda)_{11}| = |M(\lambda)_{22}| = |P(\theta + 90^\circ) \cdot M(\lambda) \cdot \mathcal{P}(\theta + 90^\circ)|.
\]

To achieve tunability over the observed range of \( \approx 15 \) nm our model clearly requires that within this range \( | \mathcal{P}^\dagger(\theta) \cdot M(\lambda) \cdot \mathcal{P}(\theta) | \) must vary with \( \lambda \) sufficiently to compensate for the wavelength-dependence of \( \exp[G(\lambda)L] \), the latter being on the order of 20–25% [12]. To prove that our doped-fiber indeed has enough birefringence dispersion, the output light from the fiber laser, now serving as a tunable source, was launched into a second piece of \( \approx 2.5 \) m of Nd-doped fiber from a similar batch, having a polarization controller, \( PC_2 \), installed along its length and yet another polarizer, \( P_2 \) at its output. The normalized transmission of the fiber + polarizer, (i.e., [Power exiting the polarizer \( P_2 \)]/[Power incident on \( P_2 \)]), was now measured as a function of the wavelength, which was changed using the polarization controller (\( PC_2 \)) in the lasing fiber; i.e., without changing the polarization of the laser output. Results are shown in Fig. 3 for three different settings of the polarization controller (\( PC_2 \)) in the second nonlasing fiber + polarizer under test. Two of the curves have sufficient slopes to create tunability over the full 15 nm range while the third one exhibits insufficient birefringence-dispersion. Moreover, in our fiber-laser the round trip in the doped-fiber is 5 m, allowing for still larger slope of the wavelength-dependent transmission \( | \mathcal{P}^\dagger(\theta) \cdot M(\lambda) \cdot \mathcal{P}(\theta) | \). Thus, the lasing medium itself serves the role the Lyot filter used in some previous configurations of tunable fiber lasers [6], [9]. The almost horizontal curve of Fig. 3 explains why some settings of the laser polarization controller experimentally yielded little tuning. Obviously, for short straight fibers, where the overall birefringence dispersion is not sufficient, tuning was not observed.

V. CONCLUSION

It was demonstrated that substantial tunability (up to 42 nm) and line narrowing can be achieved in a Nd-doped fiber.
Fig. 3. The normalized transmission of a ≈ 2.5 m doped fiber + polarizer plotted as a function of wavelength for three different settings of the polarization controller in the nonlasing fiber (PC). Tuning in the lasing fiber was obtained by varying the settings of the polarization controller of that fiber (PC') with polarizer P1 kept at a fixed angle.

The laser using the combined effects of a rotary intracavity polarizer and an in-line polarization controller. Better understanding and control of the birefringence dispersion of the doped fiber and more compact packaging may eventually result in a practical tunable fiber source for sensing and instrumentation applications.

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References


Electrically Gain-Switched Vertical-Cavity Surface-Emitting Lasers


Abstract—We report electrical gain-switching of a packaged vertical-cavity surface-emitting laser (VCSEL). Pulse durations as short as 24 ps at repetition rates up to 2 GHz were obtained from a four quantum well GaAs/AlGaAs VCSEL, which emits 0.8 mW continuous wave power in a single mode at room temperature and has a current threshold of 6 mA. Simultaneous measurement of the optical spectrum showed an almost transform limited line-width indicating ultranarrow chirp. Optical pumping with subpicosecond pulses of the same packaged devices, held at a constant electrical bias, yielded 22 ps pulses, in good agreement with the electrical pumping. Simple calculations show that the pulse duration obtained by gain-switching is limited by the design constraints necessary to operate the VCSEL continuous wave at room temperature with low-threshold current, high-quantum efficiency, and reasonable output power.

I. Introduction

The continuous wave (CW) performance of vertical cavity surface emitting lasers (VCSEL's) has been limited by excessive heating caused by the series resistance of the semiconductor Bragg mirrors through which current is typically injected [1]. However, the attributes of low-threshold current, circular output beam in a single longitudinal and