A Fiber Laser with a Comb-Like Spectrum

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Abstract—An unpolarized comb-like spectrum is emitted from a fiber laser constructed from a Nd-doped silica fiber connected to an undoped high-birefringence fiber. Depending on the overall birefringence of the high-birefringence fiber, spectral spacings of 0.8 nm to 4 nm between two adjacent wavelengths were obtained, with as many as eight simultaneous discrete peaks. No intracavity polarizing elements were used, and the observed spectral characteristics are due to parasitic reflections at the interface between the two fibers.

I. INTRODUCTION

A LASER, having an optical spectrum of a few discrete peaks (comb-like) with a spacing on the order of a nanometer, is a very useful tool for the characterization of optical systems that have wavelength-dependent properties. With such a light source it is possible to obtain a multilambda characteristic in a single measurement, and it is especially useful for systems in which operation at one wavelength can affect the device properties at other wavelengths (e.g., gain competition in optical amplifiers).

To achieve a comb-like spectrum with many simultaneously lasing lines, a very wide-gain linewidth is required, together with a proper wavelength selection mechanism. Silica-based fiber lasers, doped with rare-earth ions [1], do offer such wide-bandwidth gains (between a few nanometers to tens of nanometers) [2], and therefore, comb-like operation of these useful lasers only requires a suitable cavity design. A short-length intracavity-cavity Fabry–Perot etalon, originally intended to ensure single mode operation in multimode laser cavities [3], could provide the necessary periodic transmission characteristics. However, interline spacings on the order of a nanometer require a submillimeter-long filter, and implementation and wavelength tuning are technically difficult. A more complicated design [4] uses an intracavity multichannel wavelength division multiplexer in conjunction with an erbium fiber amplifier to achieve multiple wavelength operation at 1.55 µm. A different approach calls for the addition of an intracavity polarizer and is based on the (relatively strong) birefringence of the cavity [5]. Since different wavelengths travel with different polarizations, only that wavelength, λ1, which suffers minimum loss at the polarizer will lase [6]. However, when λ1 lases and the birefringence is strong enough, other nearby wavelengths 3n = λ1 ± mΔλ (with Δλ ≪ gain-linewidth, and m is an integer) will have the same polarization as that of λ1 and will also lase, thereby producing the required comb-like spectrum. This approach was implemented in an Alexandrite laser [4], as well as in a fiber laser [7].

In this letter we describe an all-fiber, compact, and easy-to-construct fiber laser, employing no polarizing elements, which uses a long birefringent Fabry–Perot etalon to generate a comb-like spectrum. After describing the device and its operation, a theoretical analysis is presented, followed by a few concluding remarks.

II. THE DEVICE AND ITS OPERATION

The proposed fiber laser, Fig. 1, combines an amplifying Nd-doped fiber in series with an undoped high-birefringence (HiBi) fiber and two high-reflectance mirrors, to form a Fabry–Perot cavity. Optical contact between the two fibers at the coupling point can be achieved by various means, including lenses, a small air-gap, epoxy, or oil, as long as the refractive index of the latter two is not too close to the refractive indexes of both fibers (see below). In our setup we used 3 m of 300-ppm Nd3+ doped fiber and various lengths of an undoped HiBi fiber with a specified birefringence of Δn = (n1Fast − n1Slow) = 0.4 · 10−3 at 0.8 µm. The input and output mirrors had reflection coefficients of 99% and 90%, respectively. The laser was pumped with 40 mW of an Ar laser at 514 nm (though it is also possible to use a 830-nm diode laser of similar power). Output power of the laser with a 1.6-m HiBi fiber was 0.15 mW (the low output is mostly because of the lossy connection between the fibers). The output of the fiber laser was directed into a monochromator with a resolution of 0.2 nm. The fully opened exit slit of the monochromator was imaged on a charge-coupled device (CCD) connected to an oscilloscope, so that 6 nm of the spectrum could be viewed simultaneously. To control the birefringence of the doped section, part of it was coiled to form a polarization controller (PC). For most adjustments of the polarization controller a comb-like spectrum was observed (Fig. 2). Both the spacing between adjacent wavelengths, Fig. 3, and the width of the peaks appear to be inversely related to the length of the HiBi section. By changing the refractive index of the oil at the splice we could always find a value n0 for which the comb-like structure vanished and was replaced by a quasi-continuous spectrum. Moving the refractive index of the oil away from n0 by as little as ±0.07 restored the distinct comb-like shape of Fig. 2. This observation emphasizes the reflecting role of the connection point between the two fibers. External pressure on the HiBi fiber could be used to tune the comb of wavelengths by the full interpeak

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Fig. 1. The setup of the fiber laser emitting a comb-like spectrum. $M_1$ (#1) is the high-reflector mirror, $M_2$ (#3) is the output coupler (90%), and #2 is the connection point between the doped fiber and the undoped HiBi fiber. PC$_1$ is a polarization controller.

Fig. 2. The spectrum of a Nd-doped fiber connected to a 1.2-m HiBi fiber (upper) and to a 2-m HiBi fiber (lower).

Fig. 3. The spacing between the peaks ($\Delta\lambda$) as a function of the inverse of length of the HiBi fiber.

Spacing. Similar pressure on the doped fiber or adjustment of PC$_1$ did not have any tuning effect, thus demonstrating that the locations of the peaks are independent of the birefringence of the doped section. Controlled tuning is obtained by attaching a lead zirconate titanate (PZT) modulator to the HiBi section.

III. THEORETICAL ANALYSIS AND DISCUSSION

Since the optical properties of the two fibers are slightly different, reflections at the connection point create two interacting intracavity Fabry–Perot weak resonators [3]. In analyzing this structure, we treat the HiBi fiber section together with its two end reflectors (#2 and #3) as a single complex mirror that can be described in a coordinate system attached to the slow ($S$) and fast ($F$) axes of the HiBi fiber, by the following reflection Jones matrix

$$M_1(\lambda) = \begin{bmatrix} R_S(\lambda) & 0 \\ 0 & R_F(\lambda) \end{bmatrix}$$ (1)

where

$$R_{S,F}(\lambda) = \frac{r_{25,S,F} + r_3 \exp\left[4\pi i n_{S,F} L_{\text{HiBi}}/\lambda\right]}{1 + r_{25,S,F} r_3 \exp\left[4\pi i n_{S,F} L_{\text{HiBi}}/\lambda\right]}.$$ (2)

$r_{25}$ and $r_3$ are the reflection coefficients at the interface between the two fiber sections for linear polarizations propagating from left to right in Fig. 1 and parallel to the slow and fast axes of the HiBi fiber, respectively. $r_3$ is the reflection coefficient of the right-hand high-reflectance mirror, $L_{\text{HiBi}}$ is the length of the HiBi section, and $n_S$ and $n_F$ are the refractive indexes for propagation along the HiBi axes. $R_S(\lambda)$ and $R_F(\lambda)$ are both periodic in $1/\lambda$, but since $n_S \neq n_F$ their periods $(2n_S L_{\text{HiBi}})^{-1}$ and $(2n_F L_{\text{HiBi}})^{-1}$ are slightly different. Obviously, the eigen-polarizations of this complex mirror are linear polarizations parallel to the slow and fast axes of the HiBi fiber. Thus, in the absence of birefringence in the amplifying doped section (and assuming no gain competition), these two eigen-polarizations will independently lase, each having a slightly different longitudinal mode structure, as determined by the interaction between the two cavities [3]. When the two cavities are longer than a few tens of centimeters, the longitudinal mode spacings of both lasers, being smaller than 0.01 nm, are not resolvable by our equipment, and the emitted spectrum should appear continuous, similar in shape to that from a regular fiber laser without the HiBi section.

However, residual and bend-induced stresses, as well as core ellipticity, make the doped section slightly birefringent, and the two linearly polarized waves parallel to the HiBi axes become coupled in the doped section and, as a result, lose their significance as the lasing modes [8]. Instead, other polarizations will lase. Let us consider now the wavelength dependence of the reflection coefficient from the complex mirror for incident waves which are not linearly polarized along the axes of the HiBi fiber. From (1) and (2), the (power) reflection coefficient,
\( \rho(\lambda, A_S, A_F) \), for a unit intensity incident Jones vector with components \( A_S \) and \( A_F \) is given by
\[
\rho(\lambda, A_S, A_F) = |A_S|^2 |R_S(\lambda)|^2 + |A_F|^2 |R_F(\lambda)|^2. 
\]  
(3)

But since the two terms in (3) are both periodic in 1/\( \lambda \) with slightly different periods, \( \rho(\lambda, A_S, A_F) \) is characterized by a beating frequency, which is equal to the difference between the two frequencies involved, i.e., \( f_{\text{BEAT}}(\lambda) = (2L_{\text{HiBi}}) n_S - n_F \), so that \( \rho(\lambda, A_S, A_F) \) has maxima separated by
\[
\Delta \lambda = \frac{\lambda^2}{2 |n_S - n_F| L_{\text{HiBi}}}. 
\]  
(4)

While the longitudinal modes of a typical fiber laser are spectrally spaced by only a few tens of MHz, the maxima of \( \rho(\lambda, A_S, A_F) \) are separated by some hundreds of GHz (for \( L_{\text{HiBi}} \) on the order of 1 m or less). Thus, every maximum of \( \rho(\lambda, A_S, A_F) \) is populated by many longitudinal modes, and lasing will occur at those wavelengths that suffer minimal losses, i.e., at the highest peaks of \( \rho(\lambda, A_S, A_F) \), which are spaced by \( \Delta \lambda \) of (4). The spectral width of each peak and its dependence on \( \Delta \lambda \) (i.e., on \( L_{\text{HiBi}} \)) are determined by the interaction between the homogeneous and inhomogeneous broadening mechanisms [9] and the characteristics of the composite birefringent cavity.

Following this theory, the slope of the \( \Delta \lambda \) versus \( (1/L_{\text{HiBi}}) \) best-fit line in Fig. 3 can be used to measure the birefringence of the HiBi section. Indeed, this slope gives 0.395 \( \times 10^{-3} \), which is in a very good agreement with the manufacturer’s data. Similar agreement was obtained for other tested HiBi fibers.

For most adjustments of the polarization controller, light entering the doped fiber at \#2 with linear polarizations parallel to the birefringent axes of the HiBi do not come back with the same polarization after their round trip in the doped section. For a well-designed polarization controller, though, there should be at least one adjustment for which the above-mentioned linear polarizations are eigen-polarizations for the round trip \#2 \( \rightarrow \) \#1 \( \rightarrow \) \#2. Under such conditions, the doped section behaves as if it were isotropic, and the linear polarizations parallel to the two axes of the HiBi section should lase independently, producing an output spectrum similar to that obtained from a conventional Nd-doped fiber laser [11], i.e., continuous. This case is described by (3) with either \( A_x = 1; A_y = 0 \) or \( A_x = 0; A_y = 1 \) so that no beating should be generated. This behavior was indeed observed. As expected, the introduction of a polarizer between the two fibers with its transmission axis parallel to one of the HiBi axes, while cutting one of the lasing polarization modes, does not have any significant effect on the shape of the emitted spectrum.

In conclusion, by using the polarization lasing constraints imposed by a birefringent fiber mirror, an all-fiber laser was constructed, which emits a comb-like spectrum, spanning the spectral width of a conventional fiber laser with spacing determined by the birefringence of the mirror. The laser is compact and easy to construct and tune. It can be used to characterize the spectral properties of optical systems at several wavelengths simultaneously, and to measure the beat length of polarization-maintaining fibers.

REFERENCES