Single Polarization-Mode-Beating Frequency Fiber Laser

Andrea Rosales-García, T. F. Morse, Juan Hernández-Cordero, and M. Selim Unlu

***Abstract*—We demonstrate a single-frequency fiber laser cavity that allows for measuring changes in the relative phase of two independent orthogonal polarization modes. Longitudinal-mode selection is carried out by a matched-pair of fiber Bragg gratings in a Fabry–Pérot configuration and an intracavity polarizing beam splitter allows for adjustments on each polarization independently. The polarization-mode-beating signals generated with this laser are stable over long periods of time, owing to the noise cancellation effect achieved by the common cavity shared by both polarizations. This heterodyne detection scheme allows for measuring changes in frequency as small as 5 kHz, or equivalently, wavelength changes of 40 am (attometers) which are practically impossible to resolve in the wavelength domain. The proposed configuration has possible significance as an ultrasensitive and stable polarimetric optical fiber sensor.**

***Index Terms*—Laser resonators, laser stability, optical fiber devices, optical fiber lasers, optical fiber polarization.**

I. INTRODUCTION

FIBER-OPTIC sensors based on fiber lasers have been demonstrated as polarimetric sensors for measuring strain, temperature, and current [1]–[3]. The main performance limitation of such sensors arises from the large number of longitudinal laser modes owing to the long lengths of fiber used for the cavity. Longitudinal-mode control in linear fiber laser cavities has been achieved by means of intracavity frequency selective devices; as an example, the use of saturable absorbers [3], [4] and micro-sphere resonators [5] has been shown to yield single-frequency fiber lasers. In general, all these techniques are polarization-dependent, and polarization control and/or polarization-maintaining devices are required in order to achieve stable single-frequency operation.

Fiber resonators naturally support two orthogonal polarization modes and these are used for generating the so-called polarization-mode-beating (PMB) signals [1], [2]. Since these arise from the birefringence of the fiber laser cavity, intracavity anisotropies can be evaluated upon monitoring the PMB frequencies [6]. A further important application in which PMB signals might be useful is in biological and chemical sensing, where changes in the resonance frequency of microresonators are used to detect active molecules that attach to the functionalized surface [7]. Stable PMB signals can be obtained upon limiting the number of longitudinal modes supported in the laser cavity while maintaining both polarization modes orthogonal. The latter requirement is difficult to sustain with approaches such as intracavity saturable absorbers, and long-term stability is therefore hard to achieve. In this letter, we demonstrate a fiber laser configuration from which a single and stable PMB signal can be obtained. The laser cavity includes two concatenated fiber Bragg gratings (FBGs) used as an etalon for longitudinal-mode filtering. Additionally, an intracavity polarizing beam splitter (PBS) allows for adjusting each polarization independently, thereby providing a means to obtain two single-polarization single-frequency fiber lasers sharing the same cavity. This feature offers an effective approach to eliminate common noise sources to both polarizations and thus obtain stable PMB signals. The response and stability of the PMB frequency are evaluated as a function of the optical pathlength difference between both polarizations, showing that the fiber laser can be useful for sensing applications.

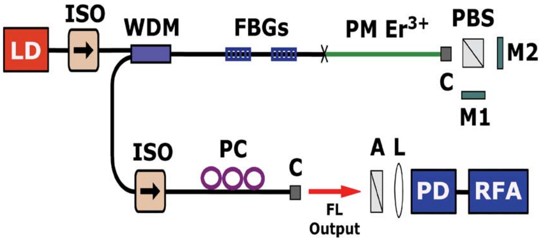

Fig. 1. Fiber laser configuration used for single PMB signal generation. The frequency of the PMB signal is monitored with a PD and RFA. Other devices include: polarization controller (PC), isolators (ISO), dielectric mirrors (M1, M2), collimators (C), polarization analyzer (A), and microscope objective (O).

II. EXPERIMENTS

Fig. 1 shows the fiber laser configuration used in our experiments. The fiber cavity is comprised of two FBGs and two dielectric mirrors. Longitudinal-mode selection is performed by means of the Fabry–Pérot etalon formed with both FBGs. The gratings are wavelength-matched ($\lambda_B \sim 1549.8$ nm), with a full-width at half-maximum (FWHM) of 60 pm, and reflectivities of 90% and 60%. The separation between the FBGs is 1 cm, thus yielding a free-spectral range of approximately 10 GHz for the etalon. A bulk PBS is placed within the cavity so that

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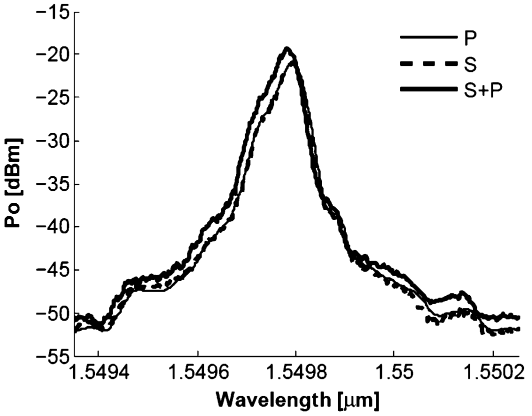

Fig. 2. Fiber laser output spectra registered with the OSA (0.06-nm resolution). The figure shows spectra obtained for dual-polarization operation ($S+P$) and for single-polarization output (S, P).

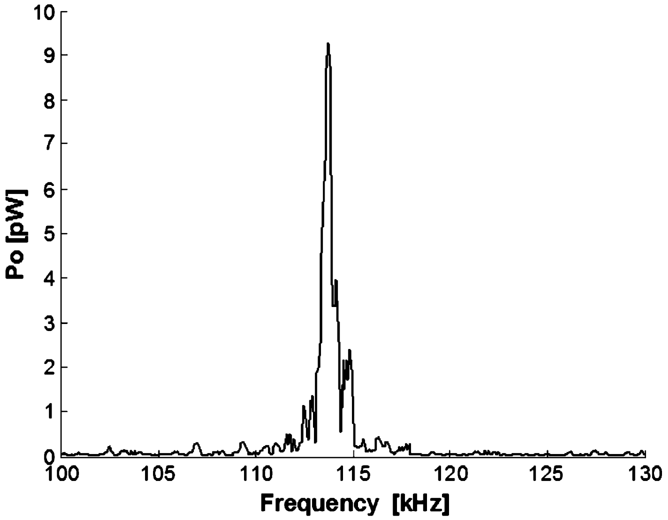

Fig. 3. Frequency spectrum of the PMB signal generated with the fiber laser.

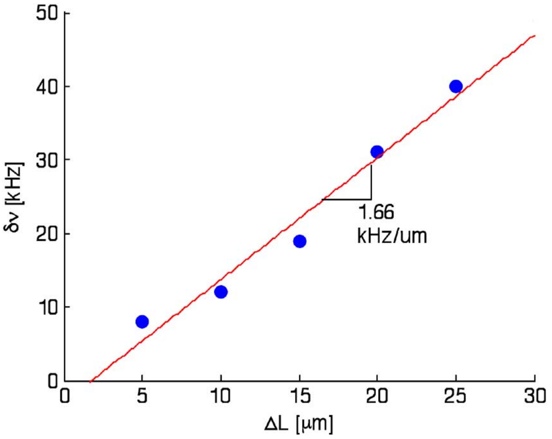

Fig. 4. PMB frequency registered as the length of one of the resonators for one polarization is changed. The straight line shows the linear fit to the experimental points.

the two orthogonal polarizations can be back-reflected separately by means of highly reflective mirrors. This allowed us to obtain two independent single-longitudinal and single-polarization mode laser cavities sharing the same noise sources. The cavity has a total length of 24 cm, including the etalon arrangement (5.5 cm), a 10-cm-long elliptical-core erbium-doped fiber (50-dB peak absorption at 1530 nm and birefringence of $\sim 10^{-4}$) whose output is collimated to traverse the PBS. Both back reflectors are placed 7 cm apart from the collimator (C, 1.5 cm long) and they can be independently adjusted by means of opto-mechanical mounts and translational stages.

A fiber coupled wavelength stabilized laser diode (975 nm) was used as the pump source. As shown in Fig. 1, the pump energy is fed into the resonator through one arm of a wavelength-division multiplexer, which also serves to extract the fiber laser output. Optical isolators are used to avoid back reflections into the laser cavity and a polarization controller is used at the output fiber. The laser output is registered either by an optical spectrum analyzer [(OSA) 0.06-nm resolution] or by a photodiode (PD) and a radio-frequency analyzer (RFA). The latter is used for monitoring the PMB signal generated after mixing both polarizations by means of a Glan–Thompson prism (A) placed in front of the PD.

III. RESULTS

Typical output spectra from the fiber laser are shown in Fig. 2 as recorded with the OSA. When using both polarizations (i.e., both back reflectors), we obtain the spectrum labeled as $S+P$, and upon blocking either of the mirrors, we register the spectra labeled as S and P. The latter spectra thus represent the output for each polarization oscillating individually within the laser cavity. To within the accuracy of the OSA, the spectral features on the two orthogonal polarizations are virtually identical. The small shift in wavelength on the $S+P$ spectrum is also within the resolution limit of the OSA (0.06 nm).

A PMB signal was observed in the RFA when the laser output was passed through the prism (A) oriented 45 ° with respect to the birefringent axes of the output fiber. The beam was focused with a lens to a high-speed photodetector (20 GHz). Fig. 3 shows the frequency spectrum recorded with the RFA: the FWHM of the signal is approximately 1 kHz and the frequency fluctuations were observed to be within a 3-kHz range when no perturbation was applied to the fiber laser cavity. The linewidth of the PMB signal shown in Fig. 3 is essentially the same as the individual linewidths of each polarization that make up this beat frequency. This is due to the longitudinal-mode filtering provided by the matched FBGs used for the etalon, which yields PMB bandwidths close to those of the longitudinal-mode-beating signals [1], as confirmed through RF measurements.

The PMB frequency depends on the phase difference between both polarizations [1], [2]; thus, if anything causes the phase to change within the laser cavity, e.g., the refractive index or the cavity length, then the frequency will change accordingly. Upon adjusting the length of one of the cavities in step increments of 2 μm , we obtained the frequency changes for the PMB signal plotted in Fig. 4. The smallest frequency change detected was as small as 5 kHz, which is equivalent to a wavelength resolution of 40 attometers, not detectable using a conventional optical spectrometer. Changes in the PMB frequency can, therefore, be associated with changes in length in the cavity for one polarization while the other remains unchanged. A similar trend for

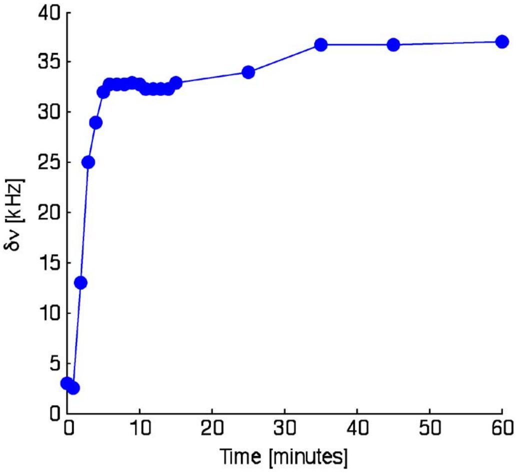

Fig. 5. Stability of the PMB frequency after the path length of one polarization is changed.

the PMB signal should be expected for changes in the refractive index of one polarization.

For sensing applications, small changes in the optical path length of one polarization will produce a change in PMB frequency. The accuracy for measuring small changes in frequency will, therefore, depend on the stability of the laser cavity. Notice, however, that our configuration is based on a dual-polarization scheme, and only the relative stability of both polarizations is relevant. Except for the section beyond the bulk PBS (see Fig. 1), both polarizations share the same cavity, and neglecting any gain anisotropy due to the elliptical core fiber, the gain medium for both waves is practically identical. Any mechanical or thermal perturbations on the cavity will, therefore, have the same effects on both polarizations and the PMB signal will be stable. The 3-kHz fluctuations in frequency mentioned earlier can, therefore, be attributed to noncommon sources of noise; in particular, thermal and mechanical effects on the mirrors and opto-mechanical mounts are likely to affect differently both arms of the fiber cavity.

The frequency stability of the PMB signal after being shifted due to a change in optical path length for one polarization was evaluated experimentally. Changing the cavity length of one polarization by approximately 10 μm resulted in the measurement shown in Fig. 5. After the fiber laser came to equilibrium, the stability between the two lasing frequencies remained of the order of 3 kHz during 1 h. This was done without any special attempts to dampen external perturbations to the system, and shows that generation of both lasing frequencies in essentially the same cavity allows for effectively subtracting the common sources of noise to both polarizations. The heterodyne mixing detection scheme thus provides a relative measurement of shifts in frequency (or wavelength) in the laser cavity, and a stable PMB signal can be generated owing to the common cavity shared by both polarizations. Thus, our fiber laser provides a means for measuring shifts in the PMB signal originated by changes in the optical pathlength between the two orthogonal polarizations in the fiber laser cavity. No evidence of mode-hoping was observed during these experiments.

Single-frequency operation in fiber lasers is generally hard to obtain with linear cavity configurations owing to spatial hole burning (SHB) effects. With our scheme, each polarization maintains an orthogonal orientation throughout the resonator and interference of both waves in the gain medium is minimized and SHB effects are restrained [4]. Independent adjustments on each polarization within the laser cavity effectively yield a single PMB signal that is stable over relatively long periods of time, and the FBG etalon further provides convenient modal selection. Notice also that the frequency separation of the two polarization modes is always smaller than the longitudinal mode spacing of the laser cavity, since the etalon allows only for adjacent polarization modes to oscillate. Single-frequency and dual-polarization operation is, therefore, possible without requiring additional stabilization techniques. These features should be of interest for sensors based on monitoring frequency changes in a fiber laser resonator.

IV. CONCLUSION

We have demonstrated a novel fiber cavity design that allows for measuring changes in the relative phase of two independent orthogonal polarization modes. The single-longitudinal mode and dual-polarization cavity were constructed using a matched-pair of FBGs in a Fabry–Pérot configuration as a longitudinal-mode filter. An intracavity PBS allowed for adjusting independently the polarization modes supported by fiber laser resonator, reinforcing single-frequency operation by minimizing SHB effects. The laser cavity can yield PMB signals that are stable over long periods of time, owing to the noise cancellation effect achieved by the common cavity shared by both polarizations. This has possible significance as an ultrasensitive, stable, optical fiber sensor with a host of different applications.

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