Frequency Instability in Er/Yb Fiber Grating Lasers due to Heating by Nonradiative Transitions

W. S. Man, Y. Z. Xu, H. Y. Tam, *Member, IEEE,* and M. S. Demokan, *Senior Member, IEEE*

Abstract— **Heating of the Er/Yb-codoped fiber lasers due to strong pump absorption was found to cause large frequency fluctuation in addition to lasing wavelength shift. Laser frequency fluctuation of up to 1.7 GHz was measured by using an absorption line of an acetylene gas cell. The large frequency fluctuation was reduced to less than 80 MHz with proper cooling of the laser.**

Index Terms— **Erbium materials, gratings, Optical fiber devices, optical fiber lasers, ytterbium materials.**

I. Introduction

ERBIUM-YTTERBIUM-DOPED fibers are excellent gain mediums for realizing single-frequency and single-polarization fiber lasers. Their broad absorption band and the more than two orders of magnitude of higher pump absorption than Er-doped fibers make them very attractive for constructing short fiber lasers [1], [2]. These lasers are promising candidates in a wide variety of applications such as dense-WDM, CATV, fiber-optic sensors and spectroscopy. Although efficient Er/Yb-doped fiber requires a nonphotosensitive phosphosilicate glass, fiber with B/Ge/Si photosensitive annulus around the Er/Yb core have been developed, so that one could write a grating directly in the fiber [3]. This eliminates the single-pass splice loss between the fiber-grating Bragg reflector and the Er/Yb-doped fiber, and permits ease of fabrication.

Typical absorption of the Er/Yb-doped fiber in 980-nm pump wavelength is about 2–3 dB/cm. This means several tens of milliwatts of pump power can be absorbed in the core of a few centimeters long Er/Yb-doped fiber, which may cause significant temperature rise in the fiber core. When an Er/Yb-doped fiber is pumped, the Yb^{3+} ions are excited from the $^3F_{7/2}$ ground level to the $^3F_{5/2}$ manifold and they transfer nearly all the energy to the $^4I_{11/2}$ level in the Er^{3+} system via a mechanism of cross relaxation between adjacent ions of Er^{3+} and Yb^{3+}. This is then followed by a fast nonradiative decay to the upper laser level $^4I_{13/2}$. Nonradiative transitions are thermal relaxations and contribute to the heating of the fiber. Since the volume of the core of the used Er/Yb fiber is very small (less than 4.3×10^{-4} mm^3 for 3-cm-long fiber), temperature rise in the Er/Yb core can be significant if the heat energy is not dissipated efficiently. Consequently, the Bragg wavelength and bandwidth of the grating written in the fiber will change according to the temperature gradient established along the length of the fiber.

We have demonstrated that Er/Yb-codoped fiber lasers that use two FBG's as reflectors not only experience lasing wavelength shift but are also unstable and may stop lasing at certain pump power due to relatively large wavelength mismatch between the two FBG's as a result of heating [4]. In this work, we report that an Er/Yb-codoped fiber laser using one FBG reflector and a dielectric broad-band mirror experienced large frequency fluctuation in additional to a large wavelength shift as in the case of DBR fiber lasers, even though it was free of the wavelength mismatching problem.

II. Heating by Nonradiative Transitions

The pump power that contributes to thermal effect in an Er/Yb fiber, $P_{\rm therm}$, can be expressed as $P_{\rm therm} = P_0 \eta_{\rm coupling} (1 - \eta_{\rm radiative})$, where P_0 is the input power, $\eta_{\rm coupling}$ is the pump coupling efficiency to the Er/Yb fiber and $\eta_{\rm radiative}$ is radiative emission efficiency of the laser. If we assume that the core is uniformly heated, which is the case under strong pumping condition, the steady-state temperature difference between the core and the cladding surface ΔT_f is given by [5]

$$\Delta T_f = T(r_0) - T(r_1) = \frac{P_{\rm therm}}{2\pi \kappa l} \ln \left(\frac{r_1}{r_0}\right) \quad (1)$$

where r_0 and r_1 are the radius of the fiber core and cladding, respectively. κ is the thermal conductivity of the fiber and l is the fiber length. In equilibrium, $P_{\rm therm}$ would also create a temperature difference between the fiber surface and the surroundings, ΔT, which can be approximated by [6]

$$\Delta T \approx \frac{P_{\rm therm}}{2\pi r_1 l \alpha_H} \quad (2)$$

where α_H is the fiber's heat transfer coefficient that includes radiation, convection and conduction. The total temperature rise in the fiber core due to $P_{\rm therm}$ is thus given by $\Delta T_{\rm Total} = \Delta T_f + \Delta T$ and can be very large. For instance, a 2.5-cm long Er/Yb fiber (with the following values: $r_0 = 2.33$ μm, $r_1 = 62.5$ μm, $\eta_{\rm coupling} = 0.7, \eta_{\rm radiative} = 0.55$, and $\alpha_H = 52$ W$\cdot$m$^{-2}\cdot$°C^{-1}) pumped with 70 mW of power from a 980-nm diode laser will have an increase in its temperature by about 40 °C. This will cause a large wavelength shift of about 0.3 nm in the FBG and will contribute to a corresponding shift in the lasing wavelength.

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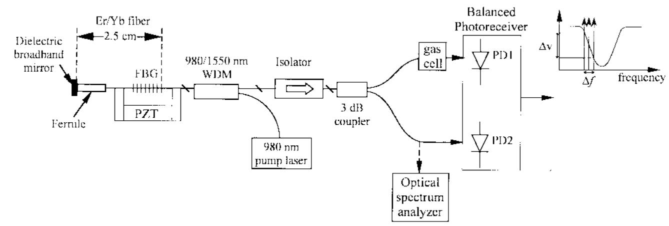

Fig. 1. Experimental setup for measuring the frequency stability of an Er/Yb-codoped fiber laser using an absorption line of an acetylene gas cell.

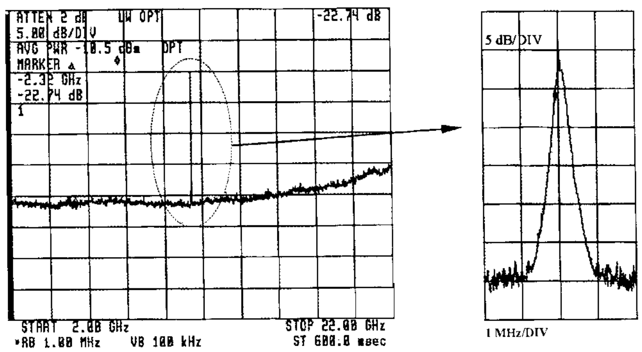

Fig. 2. RF spectrum of the Er/Yb fiber laser.

III. Experiment and Results

Fig. 1 shows the experimental setup for measuring the spectral characteristics of a Er/Yb-codoped fiber laser in DBR configuration. The fiber has a NA of 0.2, a cutoff wavelength of 1250 nm, and the absorption at 980 and 1530 nm are 2 and 0.3 dB/cm, respectively. A 2.5-cm length of the Er/Yb fiber was fusion spliced to a 980/1550-nm WDM at one end. The other end was butt joined to a dielectric broadband mirror by first gluing the fiber inside a ferrule which was polished and then epoxied to the mirror. The output coupler is a 6-mm-long grating, with 90% reflection, and was UV written into the other end of the Er/Yb fiber. The Bragg wavelength and bandwidth of the fiber grating are 1534.50 and 0.26 nm, respectively. An optical isolator was connected to the output port of the WDM to prevent any unwanted reflection back to the fiber laser. Half of the fiber laser output was passed through a gas cell filled with acetylene, via a 3-dB coupler. The gas cell is 2 cm long and the gas pressure is 760 torr. A 1.53474-μm absorption line was used for the frequency stability measurement. The FWHM spectral width of the absorption line is about 10 GHz at atmospheric pressure and the shift in absorption peak wavelength is $\sim$0.1 MHz/°C [7]; this provides an accurate and simple method for measuring frequency instability of fiber lasers.

The pump threshold and slope efficiency of the fiber laser without cooling is 4.5 mW and 8.9%, respectively, and with cooling is 4.2 mW and 10%. The linewidth of the fiber laser was measured to be about 30 kHz and was confirmed to be operating in single-frequency, single polarization regime in a separate experiment (shown in Fig. 2). The central wavelength of the fiber laser was then tuned to the slope of the absorption line (inset of Fig. 1) by applying tension to the fiber laser using a multistack PZT. Any frequency fluctuation in the laser line will be converted into amplitude modulation and can be measured accurately using a balanced photoreceiver. The balanced photoreceiver cancelled out laser-intensity noise without the need of lock-in amplifiers. The slope of the gas absorption line at 1.53474 μm was measured with a commercial external cavity tunable laser (Santec laser) to convert voltage change to frequency variation.

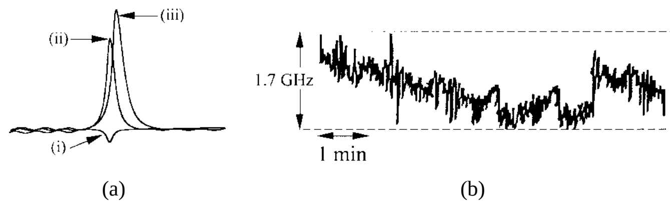

Fig. 3. Characteristics of the fiber laser without cooling. (a) Output spectra for different pump powers. (i) 1 mW. (ii) 4.3 mW. (iii) 68 mW. (b) Frequency versus time measured with the gas cell and balanced photoreceiver.

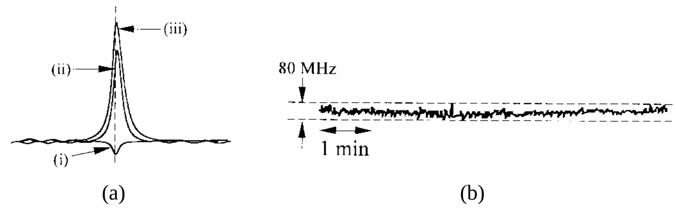

Fig. 4. Characteristics of the cooled fiber laser. (a) Output spectra for different pump powers. (i) 1 mW. (ii) 4.3 mW. (iii) 68 mW. (b) Frequency versus time measured with the gas cell and balanced photoreceiver.

Fig. 3(a) shows the spectra of the fiber laser measured as the pump power was increased from about 1 mW to about 68 mW, without cooling. At 4.5 mW of pump power, the fiber laser began to lase [trace (ii)] and continued lasing with increasing output power as the pump was increased to 68 mW. No unstable phenomenon was observed apart from the lasing wavelength shift due to the heating of the fiber. Fig. 3(b) shows that the frequency of the laser fluctuated over a range of about 1.7 GHz when the fiber was pumped with 68 mW of pump power. The long-term frequency drift is about 1-GHz peak-to-peak and the short-term frequency fluctuation is generally within 700 MHz. For this measurement, the lasing wavelength of the fiber laser was tuned back to the slope of the absorption line by tuning the PZT. This is because at this pump level the lasing wavelength shifted by about 0.3 nm. The experiment was repeated with the grating part of the fiber laser inserted into a metal ferrule to cool the fiber laser. The fiber (which has a cladding diameter of 125 μm) was not glued to the ferrule. The diameter of the hole in the ferrule is 140 μm and heat sink compound was applied in the gap between the fiber and the ferrule to aid the transfer of heat from the fiber to the metal ferrule. Stable operation was observed when the pump power was increased. No wavelength shift was measured [refers Fig. 4(a)] with the optical spectrum analyzer (resolution of 0.08 nm) when the pump power was increased up to about 68 mW. Fig. 4 (b) shows that reduction in the frequency fluctuation of the laser output was significant. Both the short-term frequency fluctuations and long-term frequency drift were measured to be less than 80 MHz, limited by the sensitivity of the photodetector. This means that the actual frequency fluctuation could be much less than 80 MHz. The resolution of this measurement can be improved by using a more sensitive photoreceiver and/or a multipass gas cell to extend the gas absorption length.

A fiber laser's frequency fluctuations are generally dominated by mechanical motion of the cavity elements and thermal drift. Mechanically, the fiber laser in both the cooled and uncooled cases has similar characteristics since the grating was not glued to the ferrule in the former case. Similar reduction in the frequency fluctuations was also observed when the fiber was cooled just by bringing a heat sink (with heat sink compound) in close contact with the grating part of the fiber laser. The large frequency fluctuations are basically caused by changes in the ambient temperature conditions. When the laser is not cooled, the temperature at the fiber core can be as high as 40 °C above room temperature. Therefore, the fiber laser which has a very small mass ($\ll 1\ \mu$g) and a relatively large surface area is extremely sensitive to small ambient temperature variations when it is not cooled. These introduce changes in the index of refraction of the fiber core and cause frequency fluctuations. Variations in the pump power will also induce large frequency fluctuations in the un-cooled fiber laser. The long-term frequency drift was caused by the air conditioning system in the laboratory which regulates itself every few minutes.

In conclusion, we have shown that Er/Yb-codoped DBR fiber laser need to be cooled to avoid the large frequency fluctuation due to the large amount of nonradiative transition that contribute to the heating of the fiber, thus making it extremely sensitive to small ambient changes.

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