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In situ cavity loss measurements of a mode-locked erbium-doped fiber ring laser by the relaxation oscillation frequency method

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We experimentally measured the cold cavity loss of a mode-locked erbium-doped fiber ring laser in situ by using the relaxation oscillation frequency method. The relaxation oscillation frequency is measured for various pumping powers and the data is fitted by the least squares method with a theoretical curve of parameters including the cavity loss. We obtained a cavity loss of 15.3 ± 0.5 dB which was found to agree with the results of direct transmission loss measurements.

I. INTRODUCTION

The cold cavity loss of a laser is an important parameter which influences many characteristics of the laser operation such as the threshold pumping power, the steady state gain, and the output power [1,2]. Especially in a mode-locked ultrashort pulse laser, the pulsewidth is determined by the steady state gain which is equal to the cold cavity loss [3]. The knowledge of the cold cavity loss is also used to investigate the dispersion behavior in an erbium-doped fiber (EDF) laser [4]. However, it is not easy to measure the cold cavity loss of a laser under operation. Several techniques are known to measure the cold cavity loss of a semiconductor laser, such as the multilength technique [5], the transparency technique [6], and the below-bandgap technique [7], but they are valid only for semiconductor lasers. The cold cavity loss can also be obtained by measuring the threshold pumping power with various output coupling ratios [8], but this method requires various output couplers with different coupling ratios or a tunable output coupler with a calibrated coupling ratio, which is not practical for common lasers. Measurement of the cold cavity loss from the relaxation oscillation frequencies for various pumping powers is known as a nondestructive simple method which can be used *in situ* for lasers under operation [9].

In this Letter, we experimentally measured the cold cavity loss of a harmonically mode-locked EDF ring laser *in situ* by measuring the relaxation oscillation frequencies while changing the pumping power. The measured value of the cold cavity loss coincided with the results obtained from direct transmission loss measurements.

II. EXPERIMENTAL

The relaxation oscillation frequency of a laser, f_r, is given by [10]

$$f_r = \frac{1}{2\pi}\left[\frac{r-1}{\tau_2\tau_c} - \left(\frac{r}{2\tau_2}\right)^2\right]^{1/2}, \qquad (1)$$

where τ_2 is the upper level lifetime of the gain medium, τ_c is the cavity decay time, and r is the pumping factor given by R/R_{th}, where R and R_{th} are the pumping rate and the threshold pumping rate. Since the pumping rate is proportional to the pumping power, r is also given by P/P_{th}, where P and P_{th} are the pumping power and the threshold pumping power, respectively. The cavity decay time is given by $\tau_c = -\tau_r/\ln V$, where τ_r is the cavity round trip time and V is the round trip transmission factor of the laser cavity describing the cavity loss including the coupling loss at the output coupler. Thus by measuring the relaxation oscillation frequency f_r as a function of the pumping power P, we can obtain the cavity decay time τ_c and hence the transmission factor V, which directly

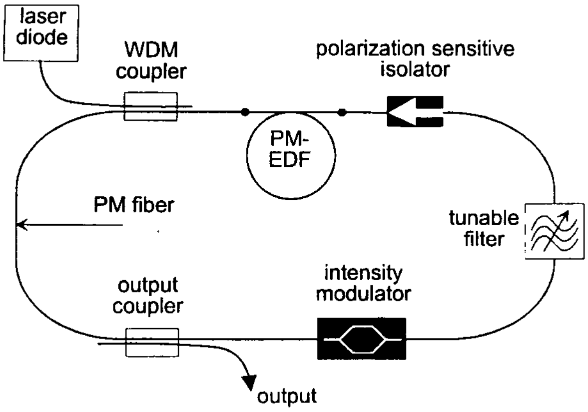

FIG. 1. Experimental setup of the harmonically mode-locked erbium-doped fiber ring laser of which the cavity loss was measured by the relaxation oscillation frequency method. The output was delivered to a photodiode with an RF spectrum analyzer to obtain the RF spectrum.

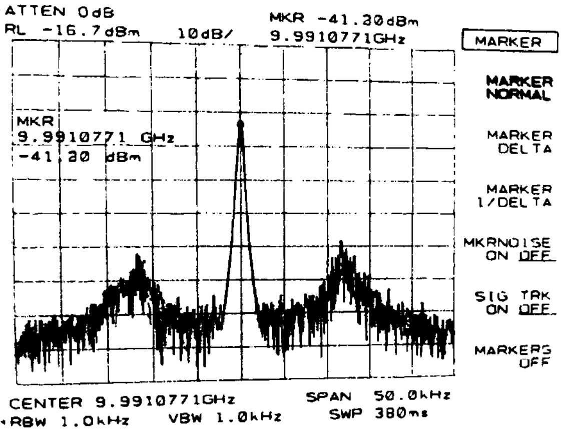

FIG. 2. Typical RF spectrum of the mode-locked laser output received by a photodiode for a pumping power of 45 mW showing sidebands resulting from relaxation oscillations. The center frequency 9.99 GHz is the mode-locking frequency and the horizontal scale is 5 kHz/div.

yields the cold cavity loss. Note that neither the actual pumping power nor the pumping rate is required and only the pumping factor $r = P/P_{th}$ is needed.

We applied this relaxation oscillation method to a harmonically mode-locked EDF ring laser [11] to obtain its cold cavity loss. The laser setup is shown in Fig. 1. The entire laser cavity was constructed of polarization-maintaining (PM) fibers to eliminate polarization fluctuations. The gain medium was a PM-EDF 10 m long and mode-locking was achieved by a Mach-Zehnder type $LiNbO_3$ intensity modulator. A tunable filter with 2.4 nm bandwidth was used for tuning the laser wavelength from 1530 to 1560 nm and a polarization sensitive isolator ensured unidirectional single-polarization operation. A 980 nm laser diode (LD) was used to pump the PM-EDF through a 980/1550 nm wavelength division multiplexing coupler. The modulator was operated at 9.99 GHz which is the 1116th harmonic of the fundamental cavity frequency 8.95 MHz corresponding to a cavity length of 23 m. The laser pulsewidth was as short as 8 psec with a linewidth of 0.4 nm and the average output power was as large as 2.1 mW. The upper level lifetime τ_2 was measured by pumping the same PM-EDF as was used in the laser with a modulated output of a 980 nm LD at intervals sufficiently longer than the lifetime (~100 ms) and then measuring the decay time of the fluorescence. We obtained a value of 8.4 ms.

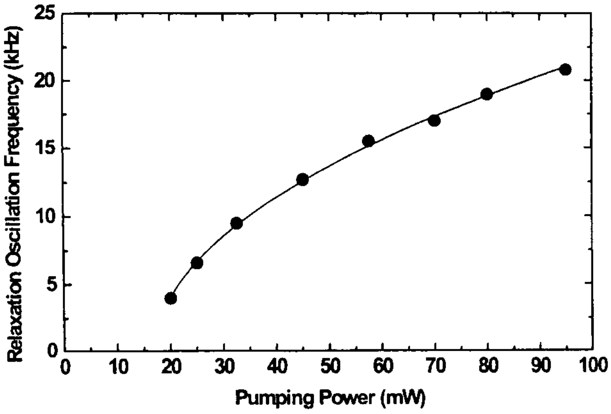

FIG. 3. Relaxation oscillation frequency measured from the RF spectrum for various pumping powers. The curve is a theoretical fit obtained by the least squares method using Equation 1. The obtained cavity decay time is 31.8 ± 0.9 ns and the corresponding cavity loss is 15.3 ± 0.5 dB.

III. RESULTS AND DISCUSSIONS

The laser output was delivered to a photodiode with an RF spectrum analyzer to monitor the relaxation oscillation frequency. It was found that slightly detuning the mode-locking frequency induced larger relaxation oscillation power without affecting its absolute frequency. A typical RF spectrum is shown in Fig. 2 for a pumping power of 45 mW. The center frequency is the mode-locking frequency 9.99 GHz and the relaxation oscillation frequency components are observed as sidebands in the RF spectrum. The relaxation oscillation frequency increased with the pumping power without any considerable change of the shape of the RF spectrum. Similar behavior was also observed for mode-locking at lower harmonics of the fundamental cavity frequency down to 8.95 MHz, which is the fundamental cavity frequency itself. Figure 3 shows the measured relaxation oscillation frequency versus the pumping power. Using the least squares method we minimized

χ^2 down to 0.0590 (kHz)^2. ($\chi^2 = \Sigma\left[f_r^{exp} - f_r^{th}\right]^2$, where f_r^{exp} is the experimental value measured by the RF spectrum and f_r^{th} is the theoretical value calculated by Equation 1.) Here P_{th} and τ_c were obtained to be 17.1 ± 0.3 mW and 31.8 ± 0.9 ns, respectively, which yields a round trip transmission factor V of 0.0298 ± 0.0030 and a cold cavity loss of 15.3 ± 0.5 dB. To check the validity of the measurements, the cavity loss was also obtained by directly measuring the transmission loss using the cutback method. The PM-EDF was cut out of the laser cavity and an LD laser beam was sent into one end of the open cavity and the output power was measured at the other end. The cutting points were made such that both splicing points between the PMF and the PM-EDF were included in the loss measurement. The measured cavity loss was 15.5 dB which coincides with our former results obtained by the relaxation oscillation frequency measurements.

The method we have used to measure the cavity loss can be generally applied to other types of lasers with relaxation oscillations. The relaxation oscillation signal can be increased if necessary by intentionally applying perturbations to the laser by mechanical vibration or thermal perturbations.

IV. CONCLUSIONS

We have experimentally measured the cold cavity loss of a mode-locked EDF ring laser *in situ* by measuring the relaxation oscillation frequencies for various pumping powers and have shown that the cavity loss measured by this method agrees well with the results obtained by direct transmission loss measurements. We believe that these results will be very useful for characterizing parameters of lasers such as pulsewidth in ultrashort pulse lasers and dispersion in EDF lasers as well as the threshold pumping power, the steady state gain, and the output power.

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