12th Optoelectronics and Communications Conference/16th International Conference on Integrated Optics and Optical Fiber Communication (OECC/IOOC2007)
Technical Digest, July 2007, Pacifico Yokohama

13C4-2

10 GHz regeneratively mode-locked SOA fiber ring laser and its linewidth characteristics

Masato Yoshida, Atsushi Ono, and Masataka Nakazawa
Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan
Tel: +81-22-217-5525, Fax: +81-22-217-5524, E-mail: masato@riec.tohoku.ac.jp

Abstract: We newly constructed a 10 GHz regeneratively mode-locked SOA fiber ring laser and measured its linewidth by changing the cavity length from 3.4 to 171 m. The linewidth was proportional to the inverse square root of the cavity length.

Introduction: Mode-locked lasers operating in the GHz region have been receiving a lot of attention with respect to their application to both ultrahigh-speed optical transmission and optical metrology including optical comb generation and opto-microwave oscillators [1]. An important characteristic of any laser used for these optical metrology applications is its longitudinal-mode linewidth. The linewidth of a cw laser was derived by Schawlow and Townes and is well known to be proportional to the inverse square of the cavity Q value [2]. Several experimental results concerning the relationship between the linewidth and the cavity Q value in mode-locked lasers have also been reported [3], [4]. Haneda et al. showed that the cavity Q value is a dominant linewidth parameter by using 10- and 40-GHz mode-locked laser diodes [3]. Ylimaz et al. showed that the linewidth is proportional to the inverse of the cavity length by using a 10-GHz mode-locked external linear cavity semiconductor laser [4]. In these reports, the lasers have short cavity lengths of less than 1 m. On the other hand, there have been no reports on the linewidth dependence on the cavity length in a mode-locked laser with a long cavity length exceeding several tens of meters.

In this paper we describe the first measurement, to our knowledge, of the linewidth of a mode-locked fiber ring laser as a function of the cavity length from 3.4 to 171 m. We discuss in detail the relationship between the linewidth and the cavity length, and indicate the limitation factor of the linewidth in a laser with a long cavity length.

Experimental Results: Figure 1 shows the structure of our mode-locked semiconductor optical amplifier (SOA) fiber ring laser, which was first reported by Kim et al. [5]. An SOA (InGaAsP) is used as a gain medium to realize a fiber ring laser with a short cavity length of several meters. The laser consists of an SOA, a 30 % output coupler, a polarization dependent isolator, a $LiNbO_3$ (LN) intensity modulator, and an optical bandpass filter with a bandwidth of 3 nm. All the fibers in the cavity are polarization maintaining to prevent any polarization fluctuation. To change the cavity length, polarization-maintaining dispersion-shifted fibers (PM-DSFs) with lengths of 3.1, 48, and 168 m are installed in the cavity. In this laser, a regenerative mode-locking technique is adopted to achieve a stable pulse operation for a long period [6].

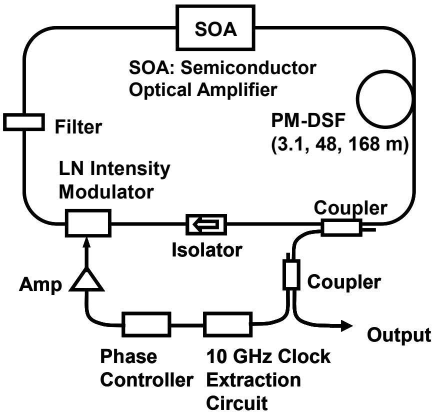

Fig. 1. 10 GHz regeneratively mode-locked SOA fiber ring laser.

Figure 2 shows the output pulse characteristics of the laser. The threshold current for laser oscillation is 120 mA and the typical output power is 0.21 mW for a driving current of 160 mA. Figure 2(a-1) and (b-1) show the autocorrelation trace and optical spectrum when the cavity length is 3.4 m (without additional DSF). The pulse width is estimated to be 8.5 ps assuming a Gaussian pulse shape. A frequency chirp is generated by the gain-saturation-induced refraction index changes in the SOA [7]. By compensating for the chirp with a conventional single-mode fiber, we reduce this pulse width to 4.4 ps. The spectral width is 0.75 nm, which corresponds to a time-bandwidth product of 0.41. This indicates that the output pulse is close to a transform-limited Gaussian pulse. Figure 2(c-1) is a 10 GHz clock spectrum with many sidebands measured with an electrical spectrum analyzer. These sidebands correspond to supermode noise. When the cavity length is increased to 51 m by installing a 48 m-long DSF in the cavity, the pulse width is estimated to be 6.8 ps assuming a sech pulse shape from Fig. 2(a-2). After chirp compensation, the pulse width is reduced to 4.0 ps. The spectral width is 0.74 nm from Fig. 2(b-2), corresponding to a time-bandwidth product of 0.37. The supermode noise is suppressed by 65 dB compared with the peak value of the clock signal as shown in Fig. 2(c-2). This can be achieved with a self-phase modulation (SPM) effect generated in the DSF and the optical filter installed in the cavity [8]. When the cavity length is 171 m with a 168 m-long DSF, the suppression ratio of the supermode noise reaches as high as 70 dB and the pulse width is narrowed to 3.6 ps by a high-pass filter effect in the SOA [9] and the soliton effect [6].

A delayed self-heterodyne detection method is used to measure the longitudinal-mode linewidth of the laser [10]. For the present measurement we used an 80 km-long fiber delay line, which corresponds to a measurement resolution

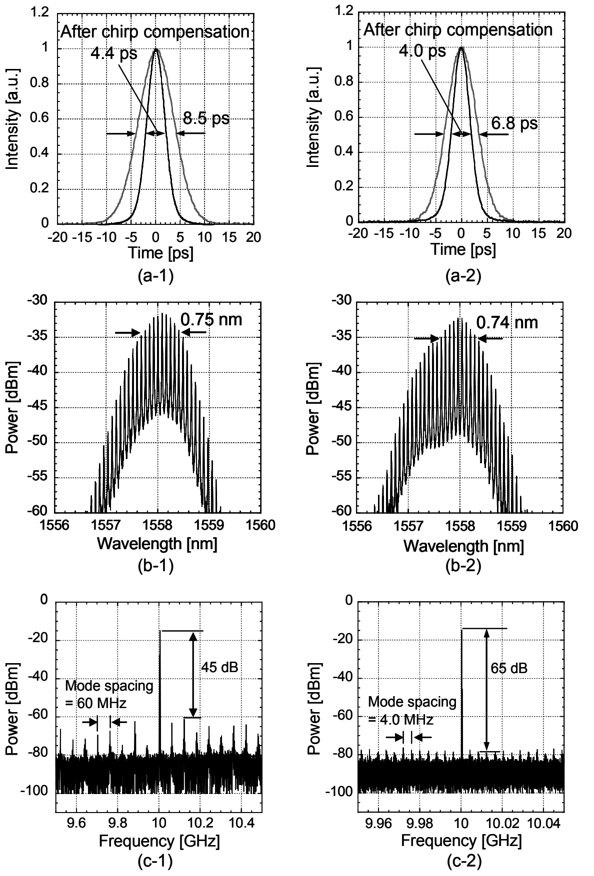

Fig. 2. Output pulse characteristics: (a-1) autocorrelation trace, (b-1) optical spectrum, (c-1) 10 GHz clock spectrum with a cavity length of 3.4 m, (a-2) autocorrelation trace, (b-2) optical spectrum, (c-2) 10 GHz clock spectrum with a cavity length of 51 m.

of 2.5 kHz. Figure 3 shows the detected beat note spectra as a function of the laser cavity length. Although a Lorentzian line shape is expected for pure white noise, environmental noise sources cause new broadening in the frequency comb lines, which adds Gaussian broadening to the line shapes [11]. Therefore we use a Voigt function fitting to simulate the RF spectra in Fig. 3. The ratio of the Gaussian and Lorentzian broadening in the Voigt function is uniquely determined by precisely fitting the wing of the self-heterodyned signal. Figure 4 plots the corresponding Voigt, Lorentzian and Gaussian linewidths versus laser cavity length, determined using the Voigt fitting procedure. The theoretical limitation of the linewidth given by the modified Schawlow-Townes formula [12] is also shown in Fig. 4 by a dotted line. Here we evaluate the theoretical limitation by replacing the cw light power in the formula with the longitudinal-mode power of the mode-locked laser, which is calculated by dividing the average laser power by the effective mode number within a 3 dB bandwidth [3]. These results show that the Gaussian component dominates the effective linewidth for all cavity lengths. Then the linewidth is almost proportional to the inverse square root of the cavity length and does not obey the theoretical limitation. This suggests that an extrinsic noise source is dominant over the observed linewidth of this laser. We attribute this to the frequency jitter of the detected beat note induced mainly by thermal or acoustic cavity length fluctuations of the laser. In this case, the actual laser linewidth is 1/√2 times the FWHM of the observed beat signal and is estimated to be 1.7 kHz for a cavity length of 171 m.

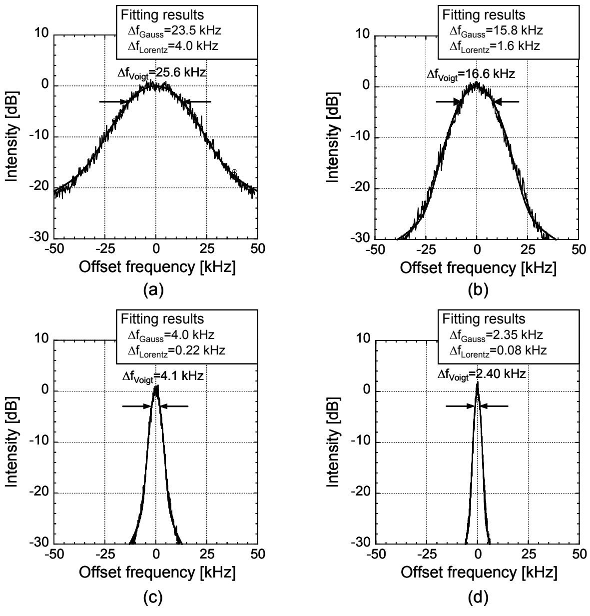

Fig. 3. Detected beat note spectra and their Voigt fittings for various cavity lengths: (a) 3.4 m, (b) 6.5 m, (c) 51 m, and (d) 171 m.

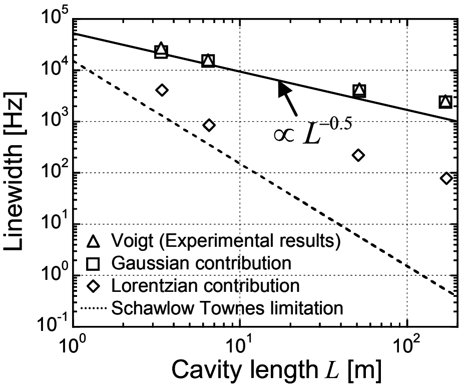

Fig. 4. Change in the laser linewidth as a function of cavity length. The Voigt function was used to fit the experimental results.

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