Actively Mode-Locked 1.5-μm 10-GHz Picosecond Fiber Laser Using a Monolithic Semiconductor Optical Amplifier/Electroabsorption Modulator

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***Abstract*—In this letter, we demonstrate a novel 10-GHz actively modelocked polarization-maintaining fiber ring laser that utilizes a single device for gain, loss modulation, optical isolation, and repetition rate adjustment. This monolithic device incorporates a semiconductor optical amplifier with an electroabsorption modulator and provides net gain of 2.1 dB. The repetition rate of the 1.5-μm picosecond pulsetrains can be tuned by 2 ppm through perturbation of the electroabsorption modulator reverse bias.**

***Index Terms*—Optical fiber lasers, optical modulation, optical solitons, phase-locked loops, pulse generation, ring lasers, semiconductor waveguides, ultrafast optics.**

I. Introduction

CONTINUAL progress in 1.5-μm ultrafast modelocked fiber lasers has led to their widespread use within the field of lightwave communication systems. Ultrafast sources fit naturally to optical time-division multiplexing (TDM) because of the need for short pulsewidths [1] and also to spectral-slicing schemes that use a single broad-band laser to drive an entire wavelength-division-multiplexed (WDM) system [2]. These applications have helped motivate extensive developments of picosecond erbium [3]–[7] and SOA-based [8]–[10] fiber lasers at repetition rates of 10 GHz and beyond. Nevertheless, these sources still exhibit limitations that prevent broader use. The erbium sources require optical pumping and tend to have long cavities which add instabilities. The SOA-based lasers can be shorter and more compact, yet have internal fiber coupling loss not present in erbium and often require strong isolation in the cavity due to large index differences between the SOA and the fiber. For all these sources, synchronizing the repetition rate to an external clock is cumbersome and typically involves complicated techniques such as high-voltage piezoelectric transducers to physically modify the cavity length. Furthermore, most of these lasers use separate discrete devices for gain, modulation, isolation, and repetition rate adjustment, which adds expense and intracavity losses to the fiber laser. In this letter, we present a novel, simple, inexpensive, and robust polarization-maintaining (PM) picosecond ring laser design that relies on a single device to provide gain, loss modulation for mode locking, directional isolation, and repetition rate tuning. This device is a monolithically integrated semiconductor optical amplifier (SOA) and 10-GHz electroabsorption modulator (EAM) [12]. The device has directional-dependent gain that provides optical isolation due to the lumped nature of the gain and loss. Also, for the first time to our knowledge, we demonstrate a technique for fast ($\sim$ MHz) tuning the repetition rate of this laser by 2 ppm through applying small perturbations to the large reverse bias voltage applied to the EAM.

Manuscript received October 29, 2001; revised April 4, 2002.

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Publisher Item Identifier S 1041-1135(02)05300-4.

II. Experimental Setup

A schematic of our laser is shown in Fig. 1. The cavity is contructed of panda PM fiber to avoid instabilities caused by polarization dependence of the SOA-EAM device and nonlinear-induced birefringence. We aligned the SOA-EAM chip to the slow axes of two-lensed antireflection-coated PM fibers to avoid fast-axis instability [11], obtaining an overall extinction ratio through the device of over 30 dB after epoxying the fibers to the chip. The laser output is extracted through a 5% PM coupler. The average group velocity dispersion inside the cavity is varied by inserting PM dispersion-shifted fiber (PM-DSF) with a zero dispersion wavelength of 1569 nm and a Kerr nonlinear factor of 3.3 $W^{-1}km^{-1}$. The rest of the cavity is constructed of standard PM fiber with a dispersion of $+16.9$ ps/nm/km at 1550 nm on the slow axis, for a total cavity length of approximately 11 m. No discrete optical filter is currently used in the cavity. Typical average output powers were 50 μW, and the pulsetrain remained in a fixed polarization state with a large extinction ratio of 23 dB.

The SOA-EAM device employs a novel spot-size converter that allows efficient coupling to a standard 9-μm mode field diameter fiber through both antireflection coated facets, yet confines the mode more tightly within the modulator and amplifier regions to enhance those affects [12]. The EAM and SOA utilize seven InGaAsP–InGaAsP quantum wells (QWs), with the EAMs QWs blue shifted so that they absorb strongly at 1550 nm when reverse biased. The entire device is situated on a thermoelectric cooler and the SOA has a length of 600 μm. The net small-signal gain of the device reaches a maximum of 2.1 dB at 1547 nm. We typically applied -5 V for the EAM DC reverse bias voltage, $V_{\mathrm{DC(EAM)}}$ in Fig. 1 and 15-V peak-to-peak RF. The extinction ratio of the modulator under these conditions is approximately 20 dB.

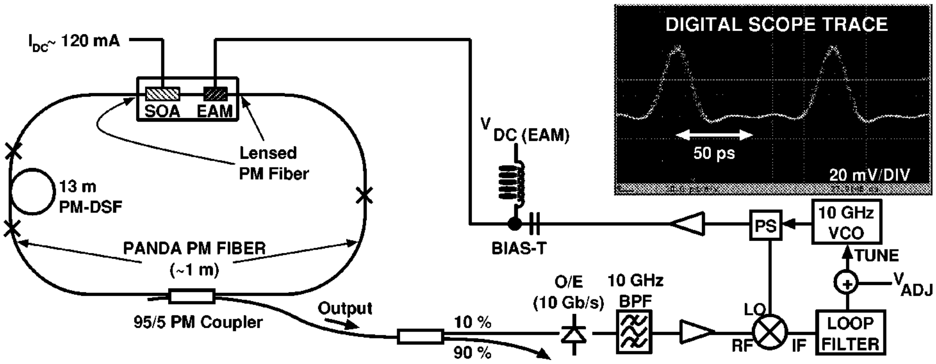


Fig. 1. Mode-locked laser schematic with digital sampling scope trace of pulsetrain.

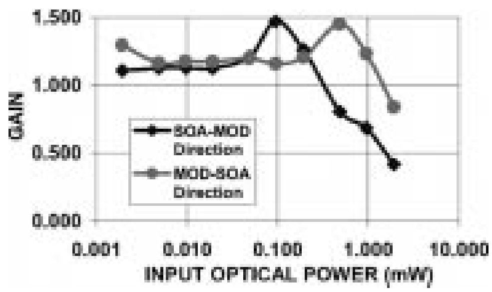


Fig. 2. Directional dependence of gain versus input optical power at 100-mA SOA drive current. Gain is expressed as a linear ratio. The laser is operated with intracavity powers where the gain is maximized.

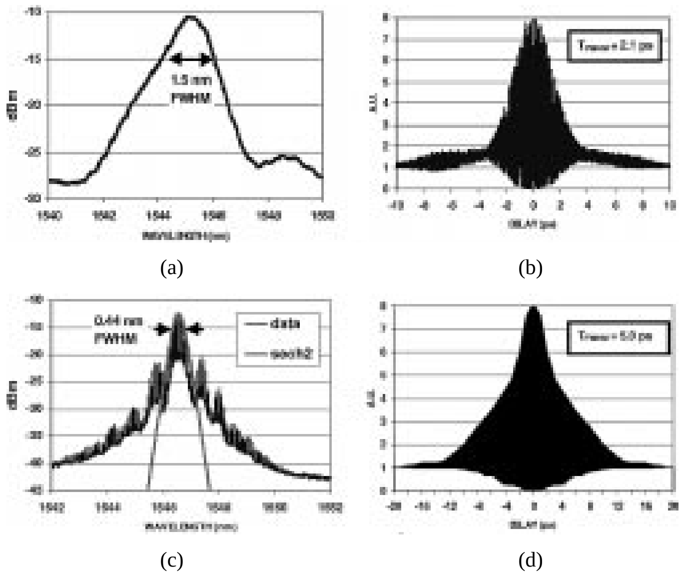


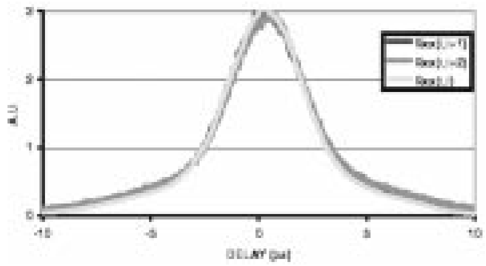
Fig. 3. (a) and (b): Optical spectrum and autocorrelation trace, respectively, for $\overline{D} = +7.0$ ps/nm/km. (c) and (d): $\overline{D} = +0.8$ ps/nm/km.

III. Results and Discussion

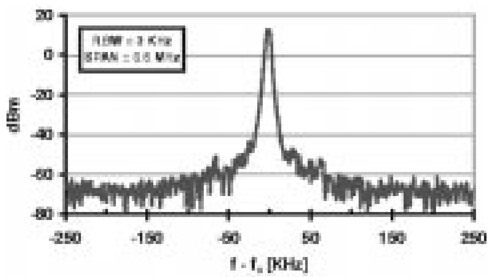
The placement of the output coupler monitors lasing in the direction such that the pulses pass first through the EAM and then through the SOA. At its maximum transmission point, the EAM induces a large loss ($\sim$ 10 dB), so if the pulse is attenuated first by the EAM it can then extract more gain from the SOA. This scenario causes less SOA gain saturation as the net gain measurements in Fig. 2 show and isolates the two lasing modes in the cavity. The isolation effect enhances the average power of the desired lasing mode by 7 dB over the undesired mode. Adding a polarizing isolator eliminates the lasing in the opposite direction, however, it does not significantly improve the mode-locking behavior, and does not enhance the output power of the desired mode. The peak in the net gain in Fig. 2 results from the saturable loss in the EAM which occurs before appreciable SOA gain saturation.

A 10-GHz clock recovery circuit was designed and built to self-seed the laser off its own harmonic. The circuit, schematically shown in Fig. 1, provides about 500 KHz of locking bandwidth. The $V_{\rm ADJ}$ signal allows coarse tuning of the drive frequency to select a particular cavity harmonic for mode locking. The voltage labeled $V_{\rm DC(EAM)}$ in can be dithered by about 25 mV from its nominal value of -5 V, thereby changing the amount of carriers flowing across the EAM junction because the peak of the RF sinusoidal modulation applied to the EAM does slightly forward bias the junction. The corresponding index change causes a shift in the rep rate of about 2 ppm and the clock recovery loop tracks this change. Dithering $V_{\rm DC(EAM)}$ by the amount stated does not fractionally change the modelocking characteristics or output power by more than 20% and is enough to compensate for variation in the rep rate due to thermal fluctuations of about 1°C.

Different average intracavity group velocity dispersion ($\overline{D}$) regimes were investigated with the laser and the data in Fig. 3 summarizes these results. For high $\overline{D}$ of $+7.0$ ps/nm/km (net round trip dispersion of 0.08 ps/nm), 2.1-ps pulses were generated with a time bandwidth product of 0.396 and intracavity soliton energies of $N = 0.14$ times the energy of a fundamental soliton; the optical spectrum shown was not taken with enough resolution to see 10-GHz cavity mode spacings. Approximately 10 m of dispersion-compensating fiber was used to reverse linear chirp in the pulses; some residual higher order chirp is responsible for the wings in the autocorrelation and the larger than expected time-bandwidth product. At lower $\overline{D}$ of $+0.8$ ps/nm/km (net round-trip dispersion of 0.0091 ps/nm) the laser approached the $N = 1$ soliton regime with a time bandwidth product of 0.314 and less chirped pulses emerging from the cavity. The autocorrelation in this case reveals a pedestal (corroborated by the pedestal in the optical spectrum), which is likely due to a combination of the nonideal extinction ratio in the EAM and the lack of strong optical filtering to favor the more narrow spectrum. In the low dispersion regime, the limited amount of self-phase modulation available for balancing group velocity dispersion actually leads



(a)



(b)

Fig. 4. (a): Noninterferometric autocorrelation ($R_{xx}(i,i)$), first-order cross correlation ($R_{xx}(i,i+1)$), and second-order cross correlation ($R_{xx}(i,i+2)$) showing $<$ 100 fs timing jitter. (b): RF spectrum of 10-GHz laser mode.

to longer, 5.0-ps pulses due to additional PM-DSF splice losses that lower the intracavity power. Additional gain in the laser and further reduction in $\overline{D}$ would likely lead to shorter pulses, while remaining near the soliton regime.

The lack of a discrete filter in the cavity allows extremely broad optical spectra to exist under conditions of lower reverse bias and lower temperature. A 3-dB bandwidth of 6–8 nm, corresponding to <500-fs pulses in the transform limit, exists under some conditions. The mode-locked 10-GHz fringes are not strongly visible in this case and linear chirp compensation could not compress the pulses to below 2 ps. Higher order chirp compensation using third-order dispersion may be a viable way to compress these pulses down to the transform limit, although the poorer modulator extinction ratio at less reverse bias and lower temperature may be inhibiting clean pulse formation. A sharp low-loss optical bandpass filter of $\sim$ 5 nm may improve upon this mode locking and enable the cavity to generate even shorter pulses.

Good timing jitter characteristics of the laser have also been observed in both dispersion regimes. The cross correlation and autocorrelation widths shown in Fig. 4(a) match to within the 100-fs measurement limit, although cross correlations between pulses further away would be necessary to fully characterize the temporal jitter. The RF spectrum also indicates excellent timing characteristics through suppression of the unmodelocked cavity harmonics by over 75 dB out to 30 GHz and good tone quality of the 10-GHz laser mode shown in Fig. 4(b).

IV. Conclusion

We have used a monolithic SOA-EAM device to demonstrate an attractive PM fiber ring laser that exhibits a high degree of functionality given the remarkably simple design. 2.1 ps were measured at an average cavity dispersion $+7.0$ ps/nm/km and the pulses closely approached the soliton regime at $+0.8$ ps/nm/km of average disperion with 5.0-ps pulses. Shorter pulses may be obtainable by enhancing the gain and optical filtering in the cavity, or by further decreasing the average dispersion. In addition to serving as gain and mode-locking elements, the SOA-EAM device provides optical isolation in the cavity and use of the clock recovery circuit to control the EAM enables fine tuning of the 10-GHz repetition rate by about 2 ppm. Future work based upon the ideas presented here could involve engineering the SOA-EAM device for enhanced output power and stronger isolation effects, exploring higher repetition rates and examing the long term mode-locking stability of such a laser.

Acknowledgment

The authors would like to acknowledge and thank Dr. J. E. Johnson for providing the SOA-EAM device.

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