Wavelength-Tunable 40-GHz Picosecond Harmonically Mode-Locked Fiber Laser Source

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***Abstract*—We demonstrate a novel 40-GHz mode-locked fiber laser that utilizes a single active device to provide both gain and mode-locking. The laser produces pulses as short as 2.2 ps, is tunable over a 27-nm band centered at 1553 nm, and exhibits long-term stability without cavity-length feedback control. The pulse train at 1556 nm was used in a 40-Gb/s transmission experiment over 45 km with a low 0.4-dB power penalty.**

***Index Terms*—Electroabsorption, integrated optoelectronics, mode-locked lasers, optical communication, optical fiber lasers, optical pulse generation, ring lasers, semiconductor optical amplifiers.**

I. Introduction

DIRECT generation of a 40-GHz pulse train using a mode-locked fiber laser offers many potential advantages over other techniques such as pulse carving, including shorter pulses, improved extinction ratio, the ability to exploit intracavity nonlinear and dispersive effects, and low timing jitter. These advantages make such sources attractive for OC-768 systems and offer the capability of achieving higher rates through optical time-division multiplexing without the need for external compression. Furthermore, they can be used in the pseudolinear regime for long-haul transmission [1].

Several impressive results for picosecond-class pulsewidths, wavelength tunability, and long-term stability have been reported for 40-GHz erbium fiber lasers actively or regeneratively mode-locked using lithium niobate modulators [2]–[4]. To make these mode-locked sources more suitable for systems applications, it is important to consider how to reduce their complexity. Semiconductor optical amplifier (SOA)-based sources have been demonstrated that achieve short pulses without using long lengths of fiber for intracavity dispersion compensation or nonlinearity, but they usually require an external, high-energy, optical pulse train for seeding [5]–[7]. Mode-locked diode lasers also offer a compact alternative [8]–[10]; however, intracavity adjustment for optimization is nontrivial in these sources, and they often require an external cavity configuration to achieve wide-band tunability. The wide tunability of fiber lasers makes them relevant for many applications beyond just data transmitters, for example, as sources in nonlinear-optics-based techniques for optical sampling and dynamic wavelength conversion. To address these issues of complexity, reliability, and tunability, we demonstrate a simple and robust 1.5-μm 40-GHz mode-locked fiber laser that relies on a single active device for both mode-locking and gain.

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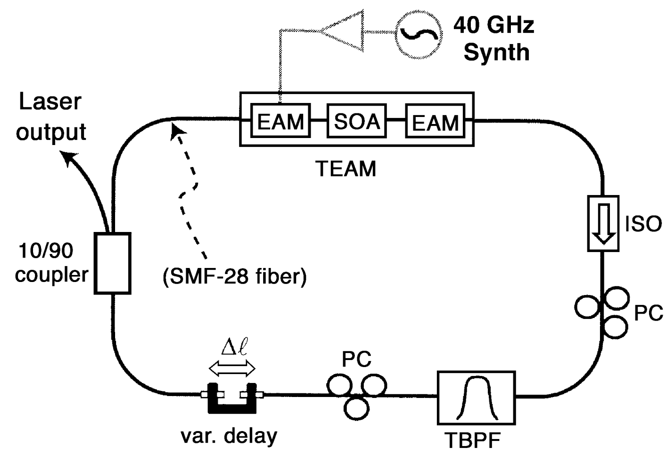

Fig. 1. Schematic of fiber-laser cavity. TBPF: tunable bandpass filter. ISO: isolator. PC: polarization controller.

The monolithic device used in this laser is referred to as a tandem electroabsorption modulator (TEAM) [11], and it contains both an electroabsorption modulator (EAM) and an SOA. This device provides both mode-locking and gain, thereby eliminating the need for multiple active components in the cavity. Previous work has shown that similar devices are well-suited for use in actively mode-locked fiber-laser sources at lower rates [12]; here, we extend the repetition rate to 40 GHz and verify the quality of the pulse train in a 40-Gb/s transmission experiment.

II. Experimental Setup

Fig. 1 shows the schematic for the TEAM-based ring laser. The fiber cavity is constructed of standard single-mode fiber (SMF-28) with a dispersion of +17 ps/nm/km at 1550 nm. A 10/90 passive splitter forms the output coupler, and an isolator restricts lasing in the undesired direction. A 9-nm tunable bandpass filter and a fine-adjustment optical delay line provide convenient wavelength and repetition-rate tuning. The TEAM device's SOA provides sufficient gain for the entire cavity. At an SOA bias current of 40 mA, which corresponds to the mode-locking threshold, the device provides a net fiber-to-fiber small-signal gain of 10 dB with a peak at 1556 nm and a 3-dB bandwidth extending from 1537 to 1568 nm. The laser exhibits a

17-MHz fundamental harmonic as a result of the 12-m cavity length. To further improve the compact and stable nature of the laser, the cavity length could realistically be reduced to approximately 1 m by shortening the fiber pigtails on the components. The cavity could also be constructed with polarization-maintaining fiber, as demonstrated in [12]. All measurements were taken with the TEAM device's thermoelectric cooler set to 20 °C.

III. Results and Discussion

The laser readily mode-locks when a reverse bias of −2-V dc and a 40-GHz 4.7-V_{p-p} sinusoid are applied to the EAM. A second EAM on the monolithic device, intended as a data encoder [11], was left open-circuited. The power exiting the output coupler is 165 μW for an SOA bias of 150 mA at a center wavelength of 1556 nm. Fig. 2(a) and (b) shows the mode-locked laser optical spectrum and autocorrelation. The optical spectrum exhibits a shoulder at shorter wavelength due to the wide filter width and a small amount of tilt across the filter passband. The optical signal-to-noise ratio, measured over a 0.05-nm bandwidth, is 33 dB on the short-wavelength side. The asymmetry of the spectrum is due to the filter, which could be optimized to further enhance the short-wavelength optical signal-to-noise ratio. Prior to the autocorrelator, a −3.1-ps/nm segment of dispersion compensating fiber (DCF) was used to reduce the chirp of the pulses emitted directly from the laser. The minimum pulsewidth measured, assuming a hyperbolic-secant pulse shape [$\text{sech}^2(t/\tau)$] shape, is 2.2-ps full-width at half-maximum (FWHM), as shown in Fig. 2(b).

The spectrum exhibits a 1.20-nm FWHM width centered at 1558 nm, corresponding to a time-bandwidth product of 0.33. Similar performance was maintained while tuning over a 27-nm bandwidth from 1540 to 1567 nm, as shown in Fig. 3. The long-wavelength limit is set by the tunable filter, and we expect the operation could be extended to approximately 1575 nm. Departure from the transform limit across the tuning band is believed to be due to higher order chirp from the EA modulator that could not be compensated by the DCF.

We analyzed the 40-GHz radio-frequency (RF) spectral, shown in Fig. 2(c), of the directly detected photocurrent from a 50-GHz p-i-n receiver to determine an upper-bound root mean square timing jitter for the laser of 140 fs over a 50-MHz bandwidth. This timing jitter differed by less than 10% on average from the jitter observed in the RF spectrum of the synthesizer (Anritsu model 69097A), and hence, we believe the jitter to be limited by the synthesizer phase noise. The RF sidemode suppression ratio was measured to be >74 dB from 0 to 50 GHz and was instrument-limited by the noise floor of the RF spectrum analyzer. The long-term laser mode-locking stability was observed by operating the laser without temperature control of the fiber cavity or cavity-length feedback control for 100 h, during which the laser ran with a high degree of stability. For one 24-h period of time, the fractional change in spectral width, output power, and center wavelength remained below 1.6%, 3.1%, and 0.1%, respectively. Over the full 100-h period, minor manual cavity-length adjustments of approximately once a day kept the fluctuations in the above parameters below ±7.5%. We believe the long-term stability is due to a combination of the large detuning range, resulting from both

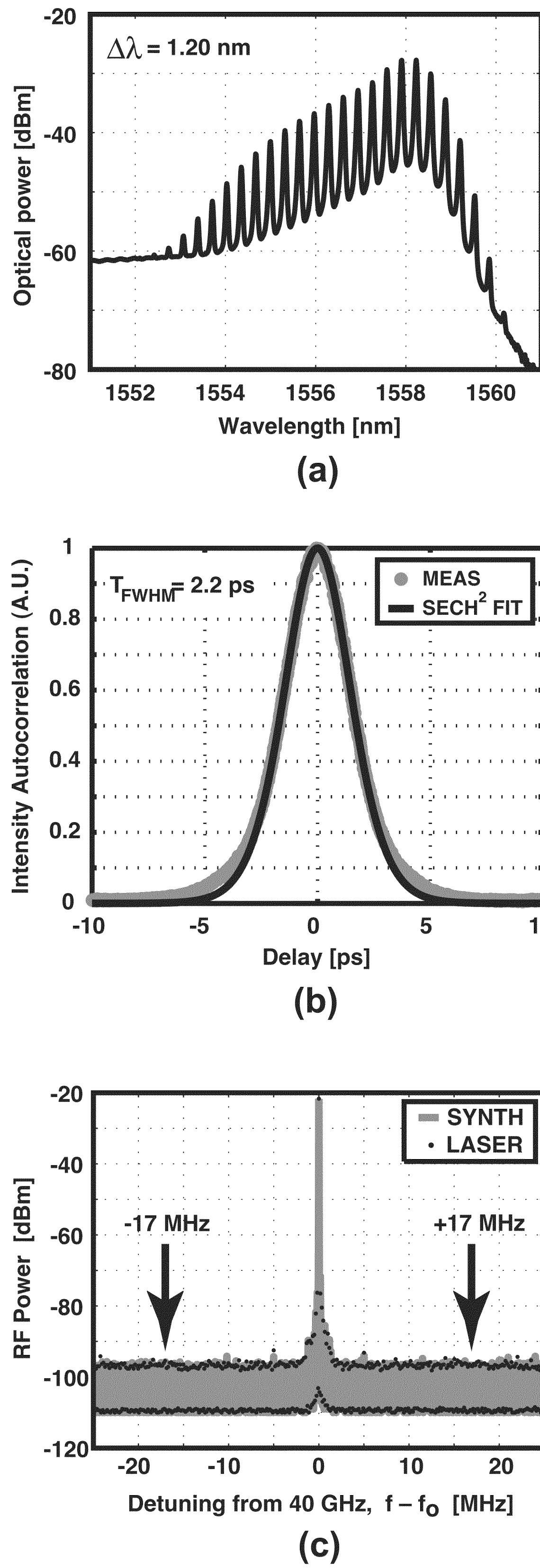

Fig. 2. (a) Optical spectrum and (b) measured/fit autocorrelation trace of mode-locked laser. (c) RF spectrum of mode-locked laser and synthesizer.

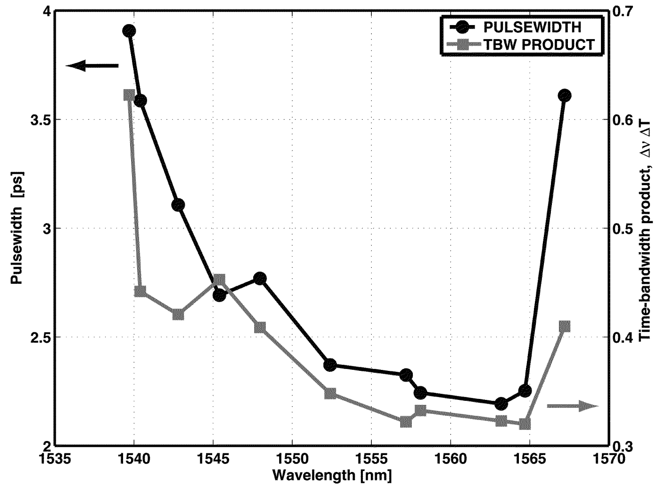

Fig. 3. Wavelength tuning characteristics of laser. Solid black line with ●: pulsewidth. Solid gray line with ■: time-bandwidth (TBW) product $\Delta\nu\Delta T$.

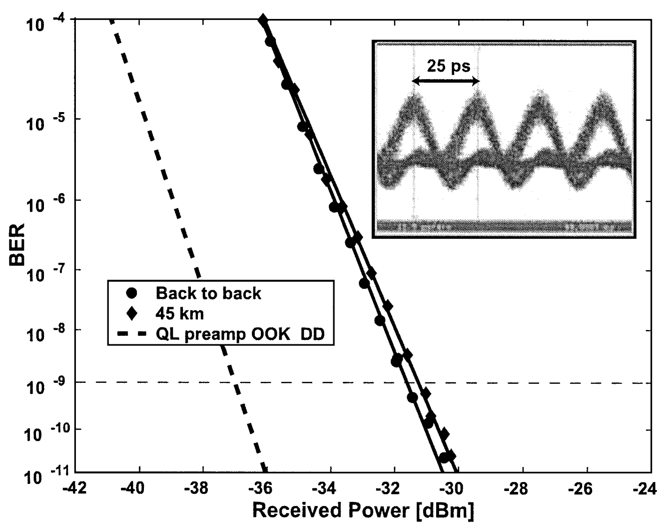

Fig. 4. 40-Gb/s bit-error-rate data of 45-km link transmission and back-to-back measurement. Dotted line is the quantum-limit for a preamplified direct-detection receiver. Inset shows eye diagram after link transmission.

the sharp nonlinear pulse carving of the electroabsorption and the fast gain dynamics of the SOA, and the short cavity length.

To establish the suitability of the source for transmission systems and to confirm that the laser does not exhibit pulse dropouts, 40-Gb/s serial bit-error-rate measurements were performed both before and after propagation through a link comprised of 38.6 km of SMF-28 and 6.4 km of DCF. With the laser tuned to 1556 nm, the pulses were immediately amplified and launched into the link; no DCF was required for chirp precompensation. 40-Gb/s pseudorandom data sequences with $2^7 - 1$ pattern lengths were applied to the pulse train using a 40-Gb/s lithium niobate modulator. The receiver was an erbium-doped fiber amplifier preamplified p-i-n photodetector operating 5 dB from the quantum limit. The observed power penalty of 0.4 dB and clear eye diagram, shown in Fig. 4, confirm that the pulses produced by the laser are of high quality and are suitable for transmission.

IV. Conclusion

We have reported an attractive means of directly generating a nearly transform-limited 40-GHz picosecond pulse train using an integrated SOA and EAM device. The source is stable, compact, and tunable over a 27-nm bandwidth. Transmission experiments over a 45-km dispersion-compensated link confirm the suitability of the pulse source as a 40-Gb/s data transmitter.

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