# Recent Results With Coupled Opto-Electronic Oscillators

X. S. Yao,[1] L. Maleki,[1] C. Wu,[2] L. Davis,[2] and S. Forouhar[2]

*We present experimental results of coupled opto-electronic oscillators (COEOs) constructed with a semiconductor optical-amplifier-based ring laser, a semiconductor Fabry–Perot laser, and a semiconductor colliding-pulse mode-locked laser. Each COEO can simultaneously generate short optical pulses and spectrally pure RF signals. With these devices, we obtained optical pulses as short as 6 ps and RF signals as high in frequency as 18 GHz with a spectral purity comparable to an HP 8561B synthesizer. These experiments demonstrate that COEOs are promising compact sources for generating low jitter optical pulses and low phase noise RF/millimeter wave signals.*

## I. Introduction

Opto-electronic oscillators (OEOs) [1,2] are a new class of oscillators for generating high-spectral-purity, high-frequency, and high-stability RF signals and optical subcarriers. We have demonstrated an OEO operating at 10 GHz with a phase noise of −140 dBc/Hz at 10 kHz from the carrier [3]. This is the lowest phase noise signal from a free-running oscillator operating at room temperature.

In OEOs previously reported on, the optical oscillation of the pump laser is isolated from the electronic oscillation. In a recent article [4], we demonstrated a coupled opto-electronic oscillator (COEO) in which the laser oscillation is directly coupled with the electronic oscillation. The coupling of the microwave and optical oscillations causes the laser to mode lock, generating stable optical pulses and microwave signals simultaneously. Because of its unique features, COEOs will find wide applications in RF communication systems, fiber-optic communications systems, and photonic analog-to-digital conversion systems.

In this article, we present three new configurations of COEOs for simultaneously generating low-jitter picosecond optical pulses and high-spectral-purity microwave signals beyond 10 GHz. We will discuss, in particular, two configurations involving integration of the laser and modulator to make compact and cost-effective COEOs.

## II. A Ring-Laser-Based COEO

In the COEO previously reported on in [4], a semiconductor optical amplifier (SOA) is used in a ring configuration to form the optical oscillation loop, and the RF oscillation loop directly feeds back to the

---

[1] Tracking Systems and Applications Section.

[2] Device Research and Applications Section.

SOA to modulate its gain. Due to the slow response of the SOA, the RF oscillation frequency is limited to below 1 GHz. To increase the RF oscillation frequency, here we use a Mach–Zehnder (M-Z) modulator in the laser oscillation loop to modulate the loop gain.

The experimental setup of the COEO is shown in Fig. 1. The output of an SOA is connected to a Mach–Zehnder modulator with a 10-GHz bandwidth. One of the outputs from the modulator is fed back to the SOA via a polarization controller to form a ring laser. The other output port of the modulator is delayed by an 800-m optical fiber, detected by a photodetector, amplified by an RF amplifier, filtered by an RF bandpass filter centered at 10 GHz, and finally coupled to the RF modulation port of the modulator to form an opto-electronic (O/E) feedback loop. Just like an OEO, when the gain of the feedback loop is larger than one, an opto-electronic oscillation will start. As described in [4], the interaction between the optical oscillation modes of the ring laser and the opto-electronic oscillation modes will force the laser to mode lock. The mode-locked laser will in turn reinforce the opto-electronic oscillation.

The experimental arrangement is similar to a regeneratively mode-locked laser [5]; however, in our case, the opto-electronic oscillation modes, which were not considered in regenerative mode locking, play a critical role. In particular, the long fiber delay for the opto-electronic loop stores the phase information of both the opto-electrical oscillation and the optical oscillation. The feedback of the stored phase information is the key to high-spectral-purity oscillations. Similarly to a conventional OEO, the phase noise of the opto-electronic oscillation, which directly translates to the jitter of the optical pulses, is expected to be inversely proportional to the time delay squared. Longer opto-electronic loop delay reduces the phase noise of the generated microwave and lowers the jitter of the optical pulses.

The pulses generated by the COEO were measured with a New Focus 40-GHz detector and a Tek CSA803 communication signal analyzer, and the result is shown in Fig. 2(a). The measured pulse width is 17 ps, limited by the rise time of the sampling head (Model SD-26). However, our preliminary autocorrelation measurement indicated a pulse width of 15 ps. On the other hand, the optical spectrum of the pulses, as shown in Fig. 2(b), has a bandwidth of 4 nm, implying that the pulses were not transform limited.

The measured RF spectra are compared with a high-performance synthesizer, Hewlett Packard (HP) 8671B, as shown in Figs. 3(a) through 3(d). Clearly, for the spectrum analyzer settings, the spectral purity of the COEO is better than that of the HP 8671B. We also measured the phase noise of the COEO, and the result is shown in Fig. 3(e). For comparison, the phase noises of the HP 8671B synthesizer and a conventional OEO with a 2-km loop length also are shown in Fig. 3(e). It is evident that, at 10 kHz

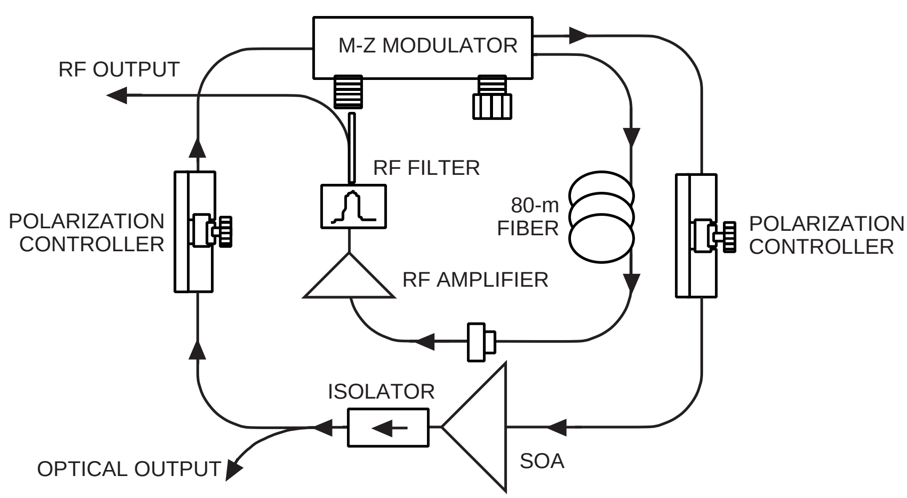


**Fig. 1. The experimental setup of a COEO constructed with an SOA and an external modulator.**

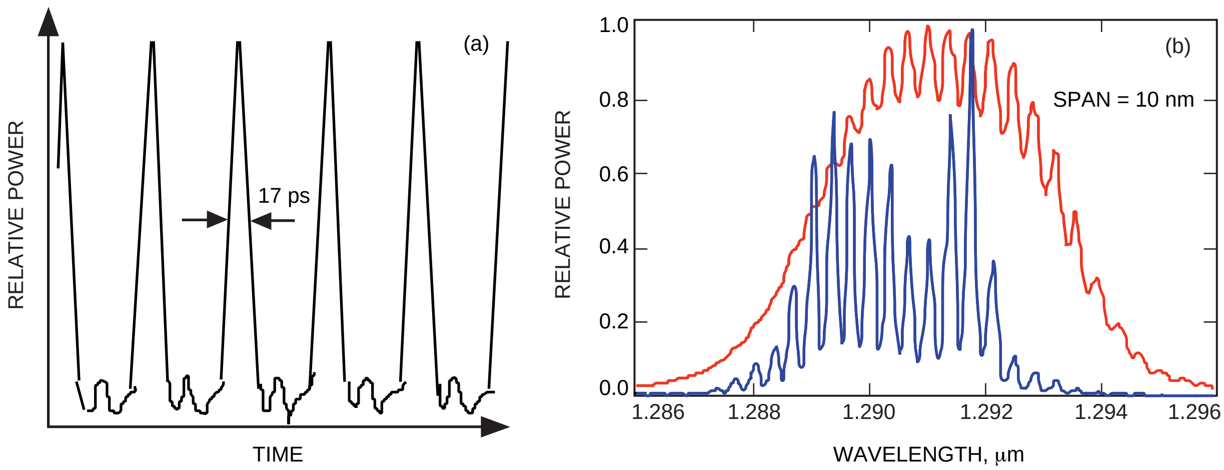


**Fig. 2. Pulses generated by the COEO: (a) time domain measurement of the optical pulses and (b) the optical spectrum of the ring laser with O/E oscillation (upper trace) and without O/E oscillation (lower trace). The resolution bandwidth (RBW) setting of the analyzer is 0.1 nm.**

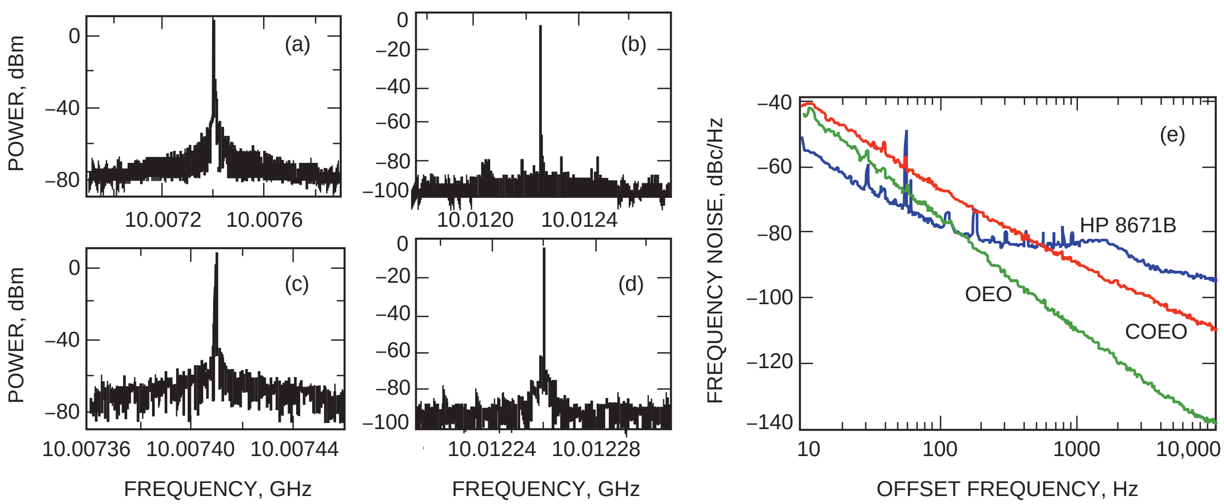


**Fig. 3. A comparison of the measured RF spectra with signals from an HP 8671B synthesizer: (a) the HP 8671B with a 1-MHz span and 1-kHz RBW, (b) the COEO with a 1-MHz span and 100-Hz RBW, (c) the HP 8671B with a 100-kHz span and 100-Hz RBW, and (d) the COEO with a 100-kHz span and 100-Hz RBW, as well as (e) a single-side-band noise comparison of the COEO, an OEO, and an HP 8671B.**

from the carrier, the phase noise of the COEO is about 10 dB better that of the HP 8671B, however, substantially larger than that of the conventional OEO. We expect to further lower the phase noise of the COEO by increasing its loop delay and employing other noise-reduction techniques.

## III. A Fabry–Perot Laser-Based COEO

A COEO also can be constructed with Fabry–Perot lasers for reduced size and cost, as shown in Fig. 4. To increase optical power and modulation speed and to reduce the chirp effect, an active gain medium is integrated with an electro-absorption modulator inside the laser cavity. Because electro-absorption modulators with a bandwidth greater than 60 GHz have been demonstrated, such an approach is promising for achieving millimeter-wave oscillations.

The integrated laser–modulator uses the identical active layer approach. The active layer of the laser and modulator is made of InGaAsP/InP multiple quantum wells with a graded index InGaAsP cladding.

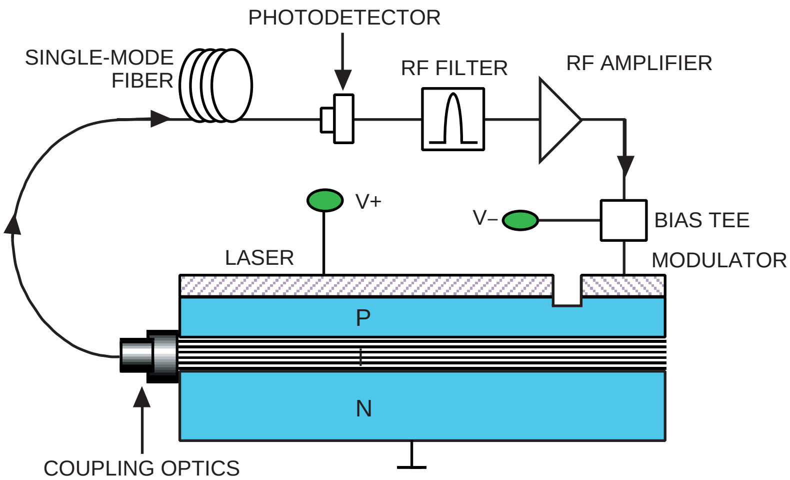


**Fig. 4. A COEO constructed with a Fabry–Perot laser and an integrated electro-absorption modulator inside the laser cavity.**

The total length of the integrated laser–modulator is about 3 mm, which gives a Fabry–Perot mode spacing of 15 GHz. The laser and modulator are electrically isolated by an etched groove in between them. The modulator has a length of less than 100 $\mu$m. The lasing wavelength is around 1350 nm. When no bias is applied to the modulator section, the laser shows a threshold current of 50 mA. The facet output power from the laser is about 10 mW at a driving current of 150 mA and 20 mW at a driving current of 300 mA. A tapered single-mode fiber is used for butt coupling, and the coupling efficiency is more than 50 percent. Figure 5 shows the laser output power (coupled into a single-mode fiber) as a function of applied voltage across the modulator. The high output power of this laser is excellent for obtaining opto-electronic oscillation.

The chip is bonded to a silicon carrier for RF testing. The RF modulation and reflection responses were measured with an HP 8607A Lightwave Network Analyzer and are shown in Figs. 6(a) and 6(b). As indicated in Fig. 6(a), the modulation response has a sharp peak at 13.6 GHz due to the resonant enhancement. When closing the opto-electronic loop, this resonant enhancement will force the opto-electronic oscillation at 13.6 GHz and cause the laser to mode lock, as explained in the first section. As can be seen, the reflection coefficient of the device is about $-15$ dB at 10 GHz and $-8$ dB at 15 GHz.

The mode-beating spectrum of a free-running laser was observed with a photodetector directly connected to an RF spectrum analyzer and is shown in Figs. 7(a) and 7(b). The strong mode beating at 13.6 GHz again indicates that, when closing the opto-electronic loop, the COEO will be forced to oscillate at 13.6 GHz and cause the laser to mode lock. The RF spectrum also indicates that the laser is free of self-pulsation under the operating condition.

The phase noise of the mode-beating signal was significantly reduced when an RF signal of 5 dBm at 13.6 GHz was applied to the electro-absorption modulator, as shown in Fig. 7(c). This indicates that the laser easily can be mode locked. Unfortunately, due to the lack of a key RF component at the time of the experiment, we were not able to close the opto-electronic loop and demonstrate COEO operation using this device.

## IV. A COEO Based on Colliding-Pulse Mode-Locked (CPM) Lasers

Colliding-pulse mode locking has been the most effective technique for generating ultrashort optical pulses in passive mode-locked dye lasers. Y. K. Chen and M. C. Wu [6] successfully demonstrated monolithic integration of a CPM laser on an InP substrate and obtained subpicosecond pulses at repetition frequencies up to 350 GHz. We demonstrate here that, by incorporating an electro-optic oscillation loop

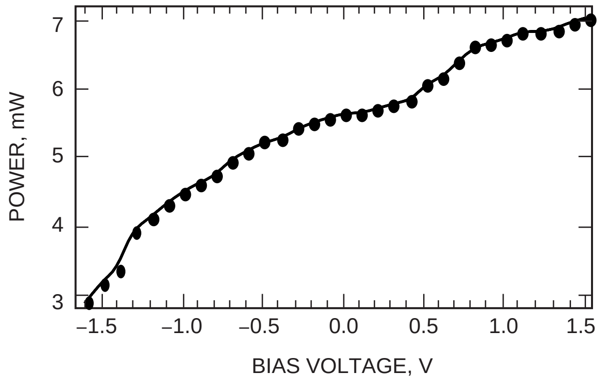


**Fig. 5. The laser output coupled into a single-mode fiber as a function of bias voltage across the electro-absorption modulator. The driving current, $I_d$, was set at 148 mA.**

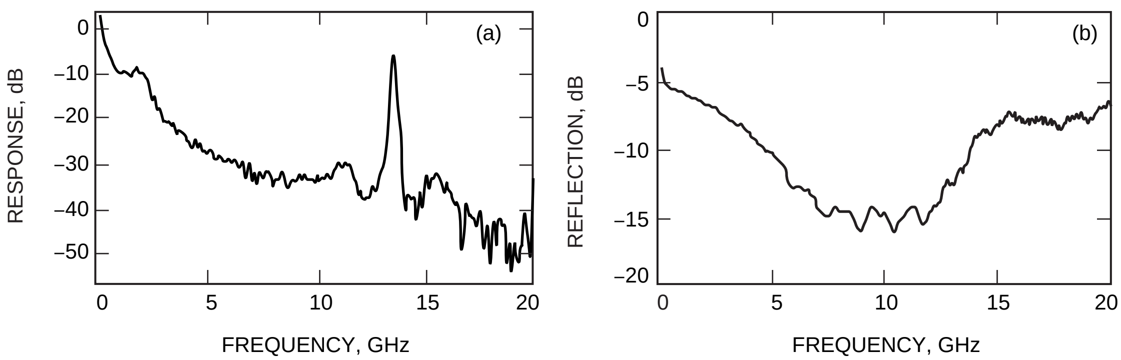


**Fig. 6. Testing measurements of the integrated laser–modulator: (a) RF modulation response and (b) RF reflection coefficient.**

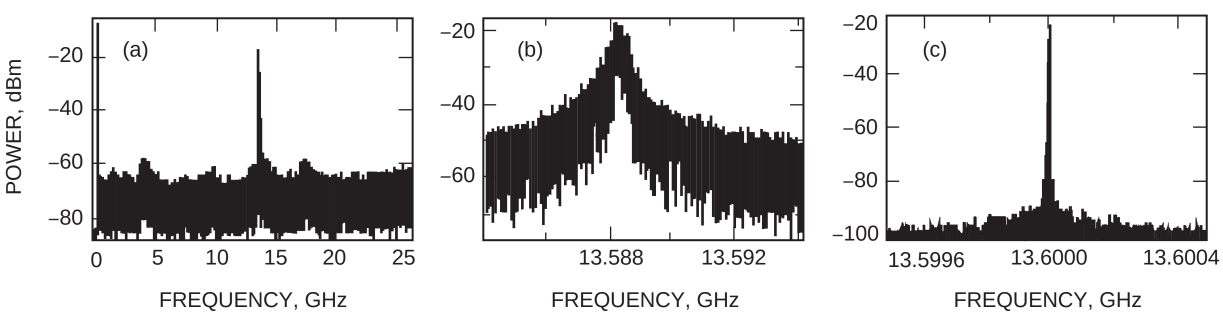


**Fig. 7. The mode-beating spectrum of a free-running integrated laser-modulator for different spectrum analyzer settings: (a) with no RF input and a 1-MHz RBW, (b) with a 10-MHz span and 100-kHz RBW, and (c) the same device with a 5-dBm RF signal at 13.6 GHz applied to the modulator, a 1-MHz span, and 300-Hz RBW.**

with a CPM laser, one can greatly reduce the phase noise and frequency jitter of the laser pulses. The effect is similar to that of injection locking the laser with an external RF source; however, the external RF source is not needed here and the generated signal quality is not limited by the external signal source. Therefore, such a CPM-based COEO can be used as a stand-alone compact source for both millimeter-wave signals and subpicosecond optical pulses.

The monolithic CPM laser used in this experiment has been cleaved from a multi-wavelength laser array designed for soliton communications [7][3] and is fabricated using two metal organic chemical vapor deposition (MOCVD) growths. The first growth is a separate confinement heterostructure (SCH) with four compressively strained ($\varepsilon = 1$ percent) quantum wells at 1.55 $\mu$m and confined on either side by 120 nm of InGaAsP ($\lambda = 1.2$ $\mu$m). After the diffraction gratings were written by direct-write electron-beam lithography and etched into the SCH region, the upper cladding and contact layers were grown. The lasers were fabricated into a 3.5-$\mu$m-wide ridge laser structure with a continuous active region. As seen in Fig. 8, the symmetric 4.6-mm-long ridge was divided into five sections with three contacts: the two end sections are 75 $\mu$m each and contain the gratings; the two gain sections are 2180 $\mu$m; and the center saturable absorber section is 50 $\mu$m. The sections are separated by four 10-$\mu$m-wide gaps, and electrical isolation of $\sim$1 k$\Omega$ is achieved between the sections by etching the InGaAs contact layer. The fabrication of a microwave ground–signal–ground (GSG) contact for the saturable absorber allows for high-frequency probing. A continuous gain region has been employed for ease of fabrication and the elimination of multiple reflections within the cavity. The individual devices have been fully packaged in a single-sided Butterfly package, including fiber coupling, a K-connector for RF input, a thermal electrical controller (TEC)/thermistor, and DC leads for the gain and grating contacts.

The threshold current for uniformly pumped devices without gratings is approximately 120 mA. Devices with gratings show thresholds of from 135 to 155 mA depending on the lasing wavelength with respect to the gain peak. When a reverse bias is applied to the saturable absorber, the devices exhibit passive mode locking for a range of gain currents and saturable absorber voltages. Typical operating currents are in the range of 165 to 210 mA and typical saturable absorber voltages are from $-0.5$ to $-2.0$ V. The devices mode lock best near threshold (as seen in [6]), and have facet powers of $\sim$1 mW at the optimal operating points. Outside the mode-locking regime of operation, the RF spectra show a distinct peak at both the cavity fundamental of 9.03 GHz and at the mode-locking frequency of 18.06 GHz. Under the proper bias conditions, the device mode locks at 18.06 GHz with removal of the continuous-wave (CW) component, and the 9.03-GHz peak is strongly (>30 dB) suppressed. However, just like other passively mode-locked lasers, the pulse jitter and phase noise are extremely high due to the high spontaneous emission noise of the laser, the complex interaction of the gain-index carrier density in semiconductors, and insufficient quality factor (Q) of the laser cavity.

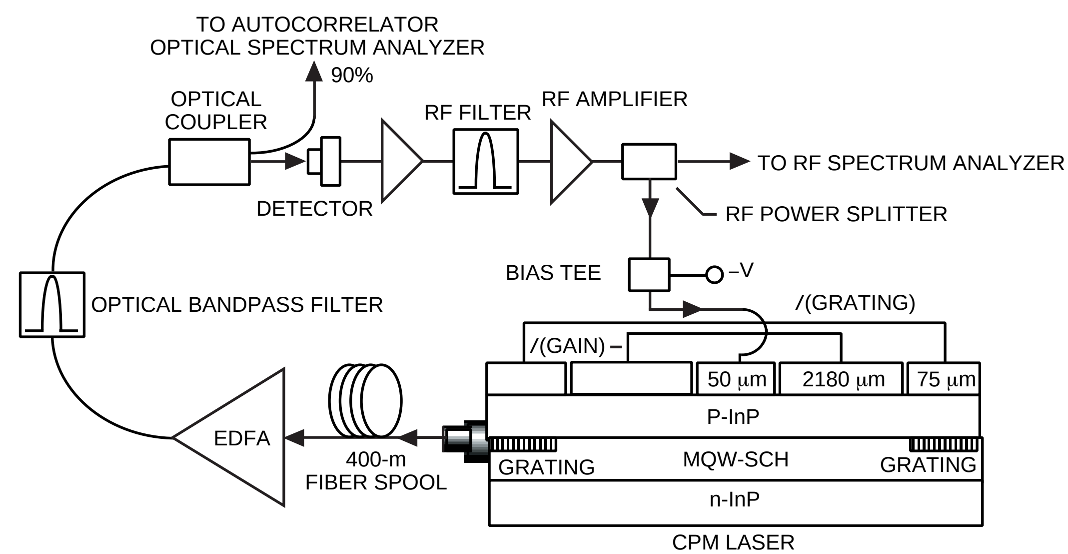


**Fig. 8. A cross-section of a colliding-pulse mode-locked laser and a COEO constructed with the laser.**

[3] L. Davis, M. G. Young, D. Dougherty, S. Keo, R. Muller, and P. Maker, "Multi-Wavelength Mode-Locked Laser Arrays for WDM Applications," submitted to *Electronic Letters*.

One may supply a sinusoidal clock signal at 18.06 GHz to the saturable absorber of the device to reduce the phase noise and jitter. However, this adds significant cost, size, and power to the device. In addition, the phase noise of the laser will be limited by the external source.

To make a stand-alone low-noise signal source, we constructed a COEO with the CPM laser, as shown in Fig. 8. The fiber spool has a length of 400 m, corresponding to an RF Q of $2.26 \times 10^5$ for a 18-GHz signal [2]. Note that the use of an $Er^+$ doped fiber amplifier (EDFA) in the loop is not mandatory for the operation of the COEO. It is used merely to boost the optical signal so that the optical pulses can be measured with an autocorrelator. We made the COEO operational even without the insertion of the EDFA in the loop.

After closing the opto-electronic loop, stable mode-locked pulses are immediately present. The spectral and autocorrelation measurements of the optical pulses are shown in Figs. 9(a) and 9(b), respectively. The spectral width, $\Delta\lambda$, is about 0.56 nm, and the pulse width, $\Delta\tau$, is 6 ps if sech [2] pulse shape is assumed [8]. Thus, the time and bandwidth product is 0.42, slightly above the transform limit of 0.32.

Stable opto-electronic oscillation also was observed with an RF spectrum analyzer at the RF output port of the COEO, as shown in Figs. 10(a) and 10(b). The mode spacing of the opto-electronic oscillation is about 487 kHz, consistent with the opto-electronic loop length. The side-mode suppression is about 21 dB. The single sideband phase noise of the 18-GHz signal can be estimated from the spectrum analyzer measurement to be −104 dBc/Hz at a 100-kHz offset and −86 dBc/Hz at a 10-kHz offset. The measured RF spectra of the COEO with or without the EDFA in the loop are about the same. Further phase noise reduction can be achieved by increasing the opto-electronic loop length and by further suppressing the side modes using the multi-loop technique [3].

## V. Summary

Three new types of coupled opto-electronic oscillators were investigated experimentally. We generated 17-ps optical pulses and a 10-GHz RF signal with low phase noise using a COEO constructed with an SOA ring laser and a Mach–Zehnder modulator. We also demonstrated the generation of 6-ps optical pulses and an 18-GHz RF signal with a COEO based on colliding-pulse mode-locked (CPM) lasers. Finally, we demonstrated that a high-power integrated laser–modulator is promising for making a COEO on a chip, greatly reducing the size, power, and cost of the device. The full demonstration of a COEO based on an integrated laser–modulator is currently under way. We anticipate that the phase noise and jitter of a COEO will reach those of an OEO (phase noise of −140 dBc/Hz at 10-kHz away from a 10-GHz carrier) in the near future.

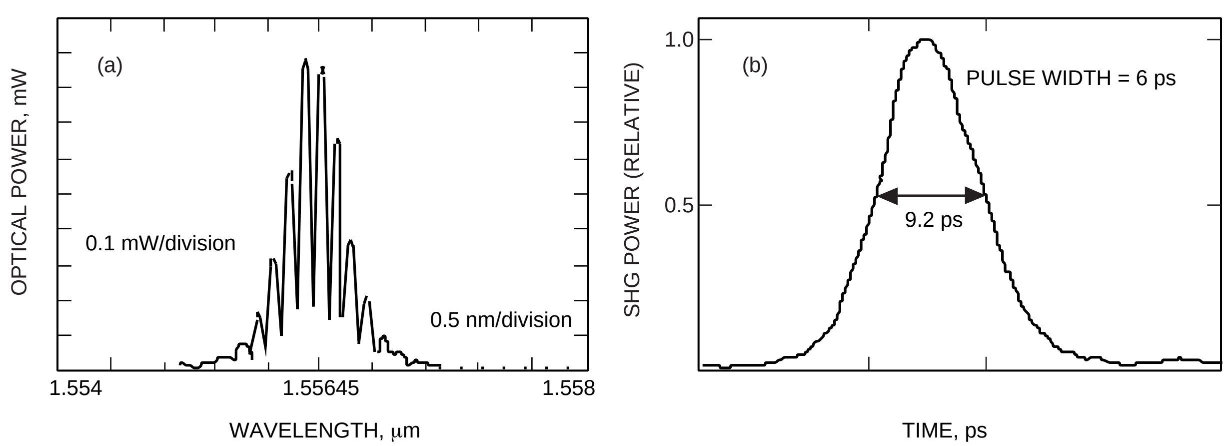


**Fig. 9. Measurements of a pulse train from a CPM laser-based COEO: (a) the optical spectrum and (b) the autocorrelation.**

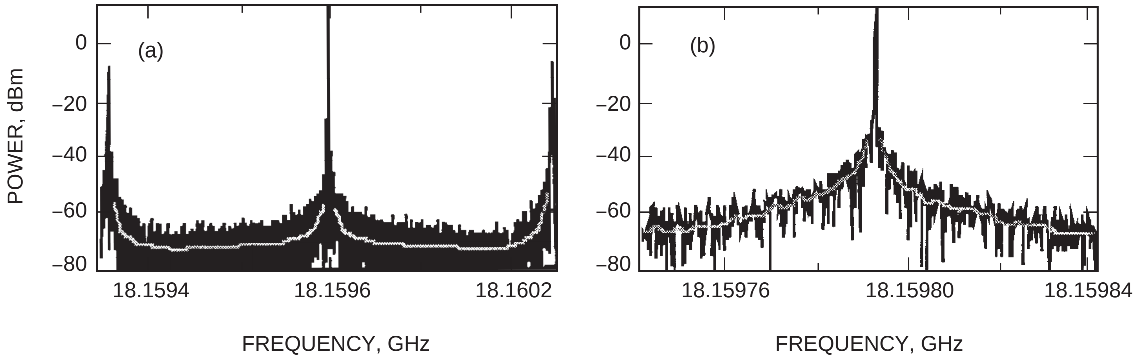


**Fig. 10. RF spectrum measurements of a COEO constructed with a CPM laser: (a) 1-MHz span and 100-Hz RBW and (b) 100-kHz span and 100-Hz RBW.**

## Acknowledgments


We thank J. Dick and G. Lutes for helpful discussions.


## References


[1] X. S. Yao and L. Maleki, "Converting Light Into Spectrally Pure Microwave Oscillation," *Opt. Letters*, vol. 21, no. 7, pp. 483–485, 1996.

[2] X. S. Yao and L. Maleki, "Optoelectronic Microwave Oscillator," *J. Opt. Soc. Am. B*, vol. 13, no. 8, pp. 1725–1735, 1996.

[3] X. S. Yao and L. Maleki, "Ultra-Low Phase Noise Dual-Loop Optoelectronic Oscillator," *OFC'98 Technical Digest*, pp. 353–354, 1998.

[4] X. S. Yao and L. Maleki, "Dual Microwave and Optical Oscillator," *Opt. Letters*, vol. 22, no. 24, pp. 1867–1869, 1997.

[5] M. Nakazawa, E. Yoshida, and Y. Kimura, "Ultrastable Harmonically and Regeneratively Mode-Locked Polarization-Maintaining Erbium Fiber Laser," *Electronic Letters*, vol. 30, no. 19, pp. 1603–1605, 1994.

[6] Y. K. Chen and M. Wu, "Monolithic Colliding-Pulse Mode-Locked Quantum Well Lasers," *IEEE Journal of Quantum Electronics*, vol. 28, no. 10, pp. 2176–2185, 1992.

[7] L. Davis, M. G. Young, and S. Forouhar, "Mode-Locked Laser Arrays for WDM Applications," Paper FA5, presented at the IEEE Summer Topical Meeting on WDM Component Technologies, Montreal, Canada, August 1997.

[8] H. A. Haus, "Theory of Mode-Locking With a Slow Saturable Absorber," *IEEE Journal of Quantum Electronics*, vol. 11, no. 9, pp. 736–746, 1975.