Coupled Optoelectronic Oscillators for Generating Both RF Signal and Optical Pulses

X. Steve Yao, Larry Davis, and Lute Maleki

***Abstract*—We present experimental results of coupled optoelectronic oscillators (COEO) constructed with a semiconductor optical amplifier-based ring laser and a semiconductor colliding pulse mode-locked laser. Each COEO can simultaneously generate short optical pulses and spectrally pure radio frequency (RF) signals. With these devices, we obtained optical pulses as short as 6.2 ps and RF signals as high, in frequency, as 18.2 GHz with a spectral purity comparable with an HP83731B synthesizer. These experiments demonstrate that COEO's are promising compact sources for generating low jitter optical pulses and low phase noise RF/millimeter wave signals.**

I. Introduction

THE coupled optoelectronic oscillator (COEO) is a novel and unique device which simultaneously produces spectrally pure microwave reference signals as in a microwave oscillator, and short optical pulses, as in a mode locked laser. The COEO is a variant of the optoelectronic oscillator (OEO)[1]–[3] which converts light energy to microwave oscillation. But unlike an OEO, which consists of a light source and an optoelectronic feedback loop, the COEO utilizes an additional optical feedback loop with an optical amplifier to simultaneously generate the light energy, as well [4]. The two feedback loops then form a coupled pair of oscillators, one producing microwave oscillation, and the other short optical pulses at the rate of the oscillation frequency in the microwave loop. Because of this coupling, the jitter in the optical pulses is determined by the spectral characteristics of the microwave signal. Since the signal in the microwave loop can have extremely high spectral purity, as already demonstrated with the "conventional" OEO, optical pulses with jitter in a few fs range may be readily generated. Such a device can clearly have important applications in a number of fields where a high level of synchronization and low jitter can improve the system performance. These include time division multiplexed and wavelength division multiplexed data communication systems, as well as other radio frequency (RF) and fiber optic systems.

The structure of the COEO is quite similar to the regenerative mode-locked laser [5]–[7]. However, the COEO differs significantly from the regenerative mode-locked lasers in the following important ways. First, the COEO can generate low phase noise microwave signals, in addition to generating optical pulses. Second, to realize the COEO we have implemented the important step of using a long optical delay line to achieve low phase noise in its microwave output, and to directly transfer the low noise characteristics of the microwave loop to the optical pulses. This step was based on the theoretical analysis and experimental verification as detailed in reference[2]. In contrast, previous regenerative mode-locking works did not consider the generated RF signal, nor did they consider any schemes within the device to lower the phase noise (jitter) of the optical pulses. We, on the other hand, have realized the connection between the phase noise of the microwave oscillation and the jitter of the laser pulses, which allows us to reduce the jitter of the optical pulses by improving the spectral purity of the microwave, or vise versa. In addition, this important connection also leads one to apply microwave techniques such as injection locking and phase locking to the electrical loop in the COEO to improve the optical pulses.

In our earlier realization of the COEO[4] we used a semiconductor optical amplifier (SOA) in a ring configuration to form the optical feedback loop. The response of this system, limited to the response time of the SOA, is slow, because the RF oscillation was directly fed back to the SOA to modulate its gain and so the microwave frequency in our system was limited below 1 GHz. In this paper we report on the performance of one scheme to overcome this inherent limitation. We also demonstrate, using a colliding pulse mode-locked laser in the optical feedback loop, a scheme which points to the realization of a COEO with small size, and low power consumption. These features are naturally desired in all high efficiency and low cost data transmission systems.

II. Ring Laser Based COEO

To increase the RF oscillation frequency, here we use a Mach–Zehnder modulator in the laser loop to modulate the loop gain. The experimental setup of this COEO scheme is shown in Fig. 1(a). The output of a semiconductor optical amplifier (SOA) is connected to a Mach–Zehnder modulator of 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 a 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 is coupled to the RF modulation port of the modulator to form an optoelectronic feedback loop. Just like an OEO, when the gain of the feedback loop is larger than one, an optoelectronic (O/E) oscillation will start. As described previously in [4], the optoelectronic feedback loop (about 800 m) is much longer than the loop length of the ring laser, resulting in a corresponding mode spacing much smaller than

Manuscript received Febuary 11, 1999; revised September 15, 1999. This work was supported by the Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration (NASA) and by the U.S. Air Force Research Laboratory.

The authors are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA.

Publisher Item Identifier S 0733-8724(00)00388-1.

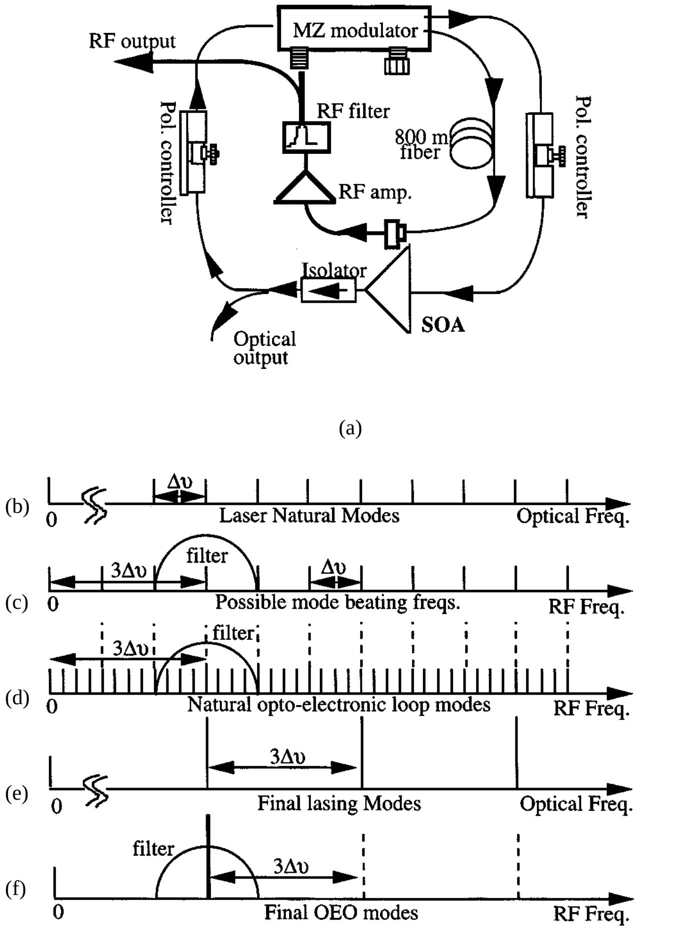

Fig. 1. (a) Illustration of a COEO constructed with a SOA and a Mach–Zehnder modulator. (b) All possible laser modes with a mode spacing of $\Delta\nu$. They have random phases in the absence of the electrooptic feedback. (c) All possible mode beat frequencies of the laser modes in the photodetector. The lowest frequency ($\Delta\nu$) corresponds to the sum of the beats between adjacent modes, the second lowest frequency ($2\Delta\nu$) corresponds to the sum of the beats between every other modes, and so on. Due to the random phases of the laser modes, these beat signals are weak and noisy. (d) All possible oscillating modes defined by the optoelectronic loop. Only those modes aligned with a mode beat frequency can get gain (or energy) from the laser. An electrical filter with a bandwidth narrower than the mode spacing of the laser selects one OEO mode ($f = 3\Delta\nu$ in the illustration) to oscillate. (e) The selected OEO oscillation then drives and mode-locks the laser, limiting the number of oscillating laser modes and forcing them to oscillate in phase. (f) The beat of the in-phase laser modes in turn greatly enhances the selected OEO oscillation.

the mode spacing of the ring laser, as shown in Fig. 1(b) and (d). The center frequency of the RF bandpass filter is chosen to be equal to an RF beat frequency of different modes of the ring laser, as shown in Fig. 1(c). The bandwidth of the filter, on the other hand, is chosen to be narrower than the spacing of the beat frequencies (equivalent to the mode spacing of the ring laser). Within the pass band, there are many OEO modes competing to oscillate. However, the winner is the mode with a frequency closest to a beat frequency of the laser's longitudinal modes, since only this (OEO) mode can get energy from the laser, as shown in Fig. 1(d). This mode is fed back to modulate the gain of the ring laser, and it effectively mode-locks the ring laser. The mode-locking makes the mode spacing of the laser equal to the frequency of the oscillating OEO mode, which is a multiple of the natural mode spacing of the laser, as shown in Fig. 1(e). Because all the oscillating modes in the mode-locked laser are forced to be in phase, all the mode beat signals between any two neighboring laser modes will add up in phase and generate a strong signal at the frequency of the oscillating OEO mode. This enhanced mode beat signal in turn provides more gain to the oscillating OEO mode and reinforces its oscillation, as shown in Fig. 1(f).

Ideally, in this setup the two oscillations can be coupled through harmonic injection locking, assuming that the nonlinearity of the modulator (or the amplifier) is sufficiently large. Therefore, in essence, the device represents harmonically coupled oscillators. In practice, because of the large frequency difference between the optical and microwave oscillation, and the limited nonlinearity of the modulator, it is difficult in general to achieve phase locking between the two oscillators, as in conventional "coupled oscillators." However, it is possible to achieve frequency locking, as described in Fig. 1.

This experimental arrangement is similar to a regeneratively mode-locked laser [5]–[7]; however here the O/E oscillation modes, which were not considered in regenerative mode-locking, play a critical role. In particular, the optoelectronic loop supports self-sustained oscillation, and the long fiber delay in the loop stores the phase information of both the optoelectrical oscillation and the optical oscillation. The feedback of the stored phase is the key to the high spectral purity oscillation. Similar to a conventional OEO, the phase noise of the O/E oscillation, which directly translates to the jitter of the optical pulses, is expected to be inversely proportional to the time delay squared. Longer O/E loop delay reduces the phase noise of the generated microwave and lowers the jitter of the optical pulses.

It should be pointed out that like any oscillators, the frequency stability $\Delta f/f$ of the COEO equals to $\Delta L/L$, where f is the oscillation frequency, Δf is the frequency variation caused by cavity length variation ΔL, and L is the total cavity length. Therefore, it is the relative length variation that is important. For optical fibers, the relative length variation is independent of the fiber length, only dependent on the thermal delay coefficient of the fiber.

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 pulsewidth is 17 ps, limited by the rise time of the sampling head (SD-26). The satellite pulses, we believe, are caused by the ringing of the photodetector. The measured average output power from the device is about 5.9 mW, and the autocorrelation measurement indicated a pulsewidth of 15 ps. 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 (HP8671B), as shown in Fig. 3(a). Clearly, for the spectrum analyzer settings, the spectral purity of the COEO is better than that of a commercial synthesizer, HP8671B. We also measured the phase noise of the COEO and the result is shown in Fig. 3(b). For comparison, the phase noise of HP8671B synthesizer and a conventional OEO with 2 km loop length are also shown in Fig. 3(b). It is evident that at

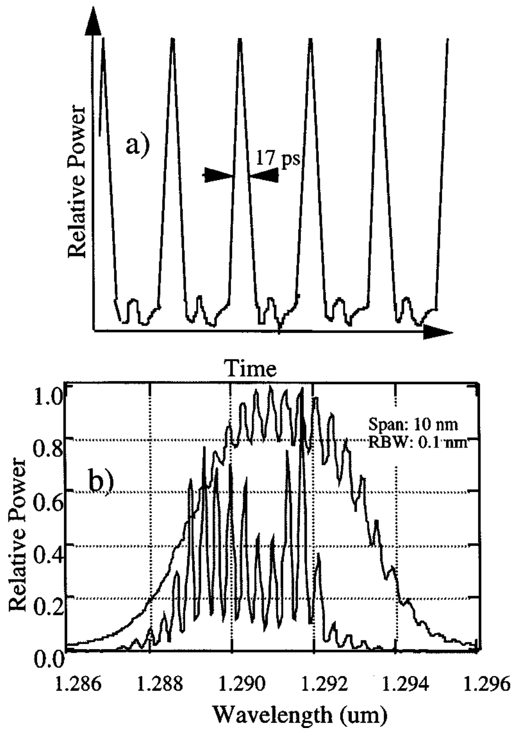

Fig. 2. (a) Time domain measurement of the optical pulses. (b) Optical spectrum of the ring laser with (upper curve) and without optoelectronic oscillation.

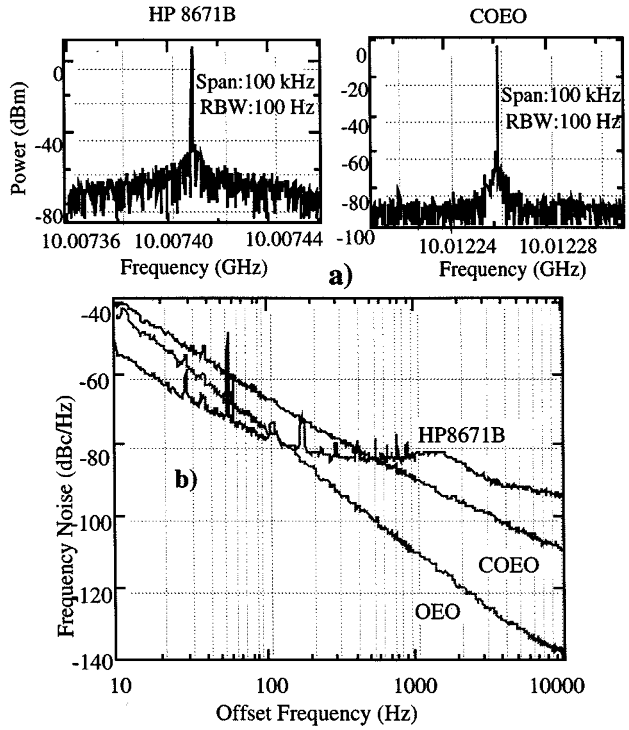

Fig. 3. (a) Measured RF spectra of the COEO output at different spectrum analyzer settings and the comparison with a signal from an HP8671B synthesizer. (b) Single sideband phase noise comparison of the COEO, an OEO and an HP 8671B synthesizer at 10 GHz.

10 kHz from the carrier, the phase noise of the COEO is about 10 dB better that of HP8671B, but substantially larger than that of the conventional OEO.

III. COEO Based on Colliding Pulse Mode-Locked (CPM) Lasers

We have previously demonstrated the OEO with an integrated DFB laser and modulator module in an attempt to point toward a chip-based OEO with high-performance, small-size, and low-power consumption, suitable for space and commercial telecommunication applications. To develop yet a lower cost version, a multimode semiconductor laser based COEO should be considered seriously. The ideal multimode laser for this application should have high optical power and good mode-locking characteristics.

Colliding pulse mode-locking (CPM) has long been considered the most effective technique for generating ultra-short optical pulses in passive mode-locked dye lasers. Recently, Chen and Wu [8] applied CPM to semiconductor lasers, and successfully demonstrated CPM lasers integrated on a single piece of semiconductor. Their laser produced subpicosecond pulses at repetition frequencies up to 350 GHz. Here we demonstrate that by incorporating an electrooptic oscillation loop with a CPM laser to form a COEO, one can greatly reduce the phase noise and frequency jitter of the laser pulses. This is similar to mode-locking the laser with an external RF source; however the external RF source is not needed here and the generated signal quality is only limited by the performance of the OEO. Therefore, such a CPM based COEO can be used as a stand-alone, compact source for both millimeter (mm)-wave signals and sub-picoseconds optical pulses.

In our experiments, 4.6-mm-long monolithic CPM lasers fabricated by two MOCVD growths were used. The first growth was a separate confinement heterostructure (SCH) with four compressively strained ($\varepsilon = 1\%$) quantum wells at 1.55 µm and confined on either side by 1200 Å of InGaAsP ($\lambda = 1.2$ μm). 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-μm wide ridge structure with a continuous active region. The fabrication of a microwave ground-signal-ground (GSG) contact for the saturable absorber allowed for high frequency probing. Further details of the fabrication are given elsewhere [9], [10]. Individual mode-locked lasers were incorporated into a fiber pigtailed butterfly package with a K-connector for application of a microwave signal to the saturable absorber of the mode-locked laser. The package contains a TEC cooler and thermistor, and requires temperature control for stable mode-locking. All measurements shown here are for a temperature of 20 °C.

The threshold current of the laser in the device described above was about of 135 mA. Typical operating currents of the device are in the range from 165 to 210 mA, with typical saturable absorber voltages in the range from 0.5 to –2.0 V. When a reverse bias is applied to the saturable absorber, the device exhibits passive mode-locking for a range of gain currents and saturable absorber voltages. It mode-locks best near threshold (as seen in [6]), and has an average facet power of ~1 mW at the optimal operating points. Outside the mode-locking regime of op-

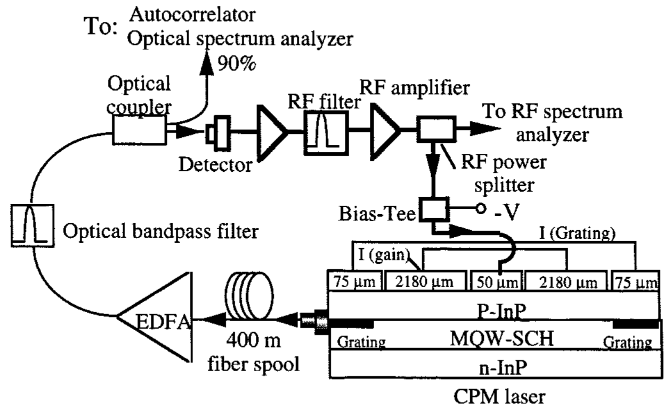

Fig. 4. The cross-section illustration of a colliding pulse mode-locked laser and a COEO constructed with the laser. The laser has two gain sections of 2.18 mm each separated by a 50-μm saturable absorber, which was also used as an electroabsorption (E/A) modulator. The gratings (75 μm each) on the laser were written to select laser's wavelength more precisely.

eration, the RF spectra shows 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 the 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 Q of the laser cavity.

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 cost, size, and power consumption to the device, significantly. In addition, the phase noise of the laser will be limited by the external source. In practice, a stand-alone RF/optical pulse generator is highly desirable. To make such a low noise and low cost signal source, we constructed a COEO with the CPM laser, as shown in Fig. 4. The fiber spool had a length of 400 m, corresponding to a $Q(= 2\pi\tau f)$ of 2.26 × 10^5 for a 18-GHz signal. Note that the use of the Er^+-doped fiber amplifier (EDFA) in the loop is not mandatory for the operation of the COEO. It is used because of the relatively low optical power (~0.1 mW) in the fiber from the CPM laser. We made the COEO operational even without the insertion of the EDFA in the loop, but with somewhat higher phase noise.

After closing the optoelectronic loop, stable mode-locked pulses are immediately present. The spectral and autocorrelation measurements of the optical pulses are shown in Fig. 5(a) and (b) respectively. The spectral width $\Delta\nu$ is about 0.6 nm and the pulsewidth $\Delta\tau$ is 6.2 ps if a sech^2 pulse shape is assumed. The time and bandwidth product is thus 0.445, slightly above transform limit.

Stable optoelectronic oscillation was also observed with a RF spectrum analyzer at the RF output port of the COEO, as shown in Fig. 6(a). The mode spacing of the O/E oscillation is about 487 kHz, consistent with the O/E loop length, and the side-mode suppression is about 21 dB. To increase the side-mode suppression and improve the phase noise, an interferometric single mode selection configuration [3] was implemented. As shown in Fig. 7, the optical signal out from the EDFA is first split by a 3 dB optical coupler into two paths. The first path passes though a 90% coupler and is received by a photodetector PD1. The detected RF signal then passes through a RF phase shifter before

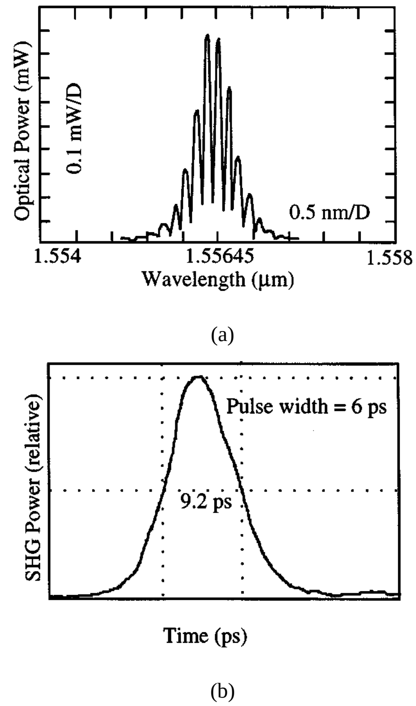

Fig. 5. (a) The optical spectrum of a pulse train from a CPM laser based COEO. (b) The autocorrelation measurement of the pulse train.

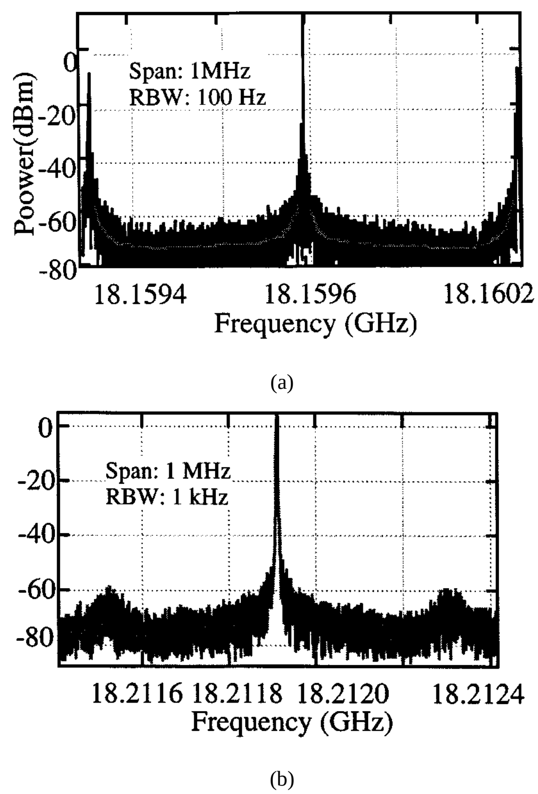

Fig. 6. (a) RF spectrum of a single loop COEO of Fig. 4. (b) RF spectrum of a double loop COEO of Fig. 7. About 40 dB of side mode suppression improvement is evident.

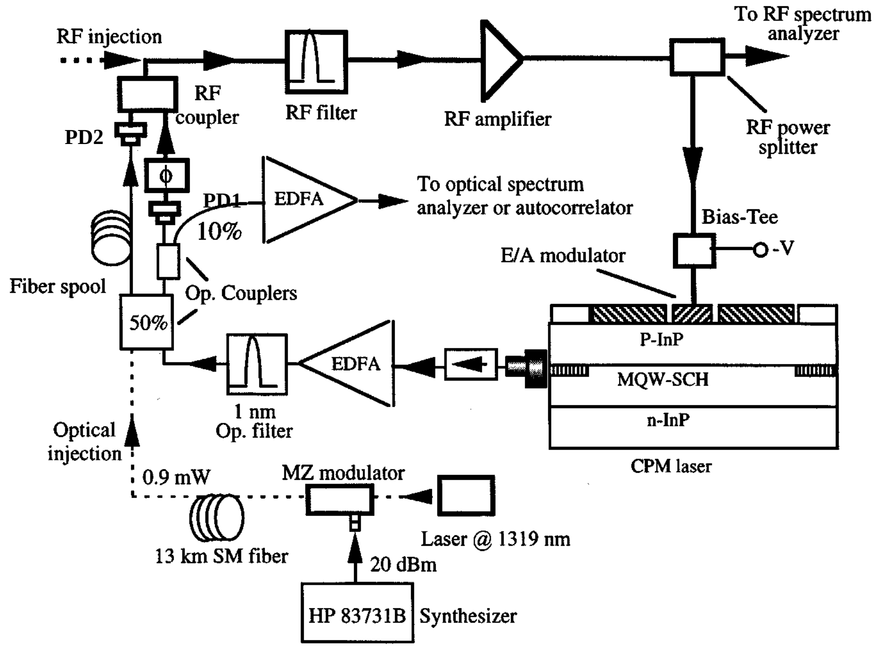

Fig. 7. CPM laser-based COEO with a built-in RF interferometer for single-mode selection. The dotted lines shows the arrangements for both RF injection locking and optical injection locking.

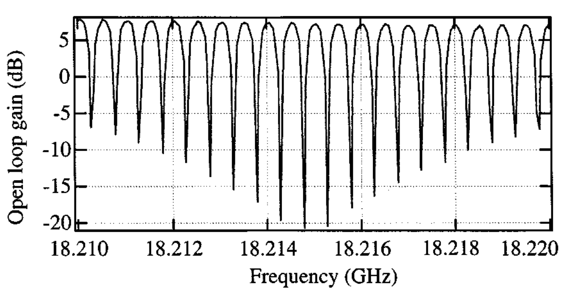

Fig. 8. The open loop gain of the CPM based COEO of Fig. 7. The periodic variation is due to the RF interferometer in the COEO loop and is responsible for improved single-mode performance (higher carrier to side-mode ratio).

entering a RF combiner. The second path for the optical signal first passes through a fiber spool before being received by another photodetector PD2 and the converted RF signal then interferes with the other RF signal from PD1 at the output of the RF combiner. The interference peaks provides additional frequency discrimination for mode selection. By adjusting the RF phase shifter, the transmission interference peaks from the RF combiner can be shifted in frequency. For the best result, the RF powers in the two paths should be approximately the same. Fig. 8 shows the open loop gain of the COEO of Fig. 7 as a function of frequency, measured with a HP8703A network analyzer. As expected, sharp interference peaks are present. The additional frequency discrimination provided by the sharp interference peaks is responsible for the additional ~40-dB side-mode suppression, as shown in Fig. 6(b).

Fig. 9(a) shows the phase noise of the COEO with different loop lengths as a function of offset frequency from the carrier, as compared with the phase noise of a low noise HP 83731B synthesizer. As indicated in the figure, the phase noise of the COEO at around 10 kHz is lower than that of the synthesizer.

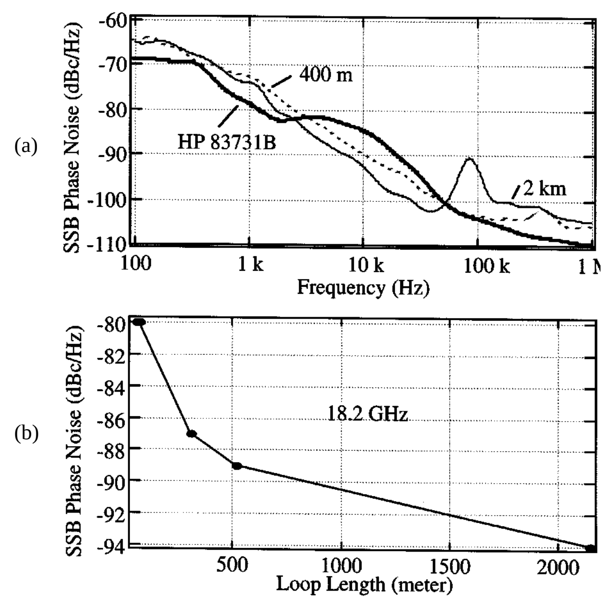

Fig. 9. (a) Single sideband (SSB) phase noise of the COEO with 400 m and 2 km loop lengths as a function of frequency offset from the 18.2 GHz carrier. The SSB phase noise of an HP83731B synthesizer at 18.2 GHz was also shown for comparison. (b) SSB phase noise at 10 kHz from the carrier of the COEO as a function of the loop length.

The phase noise "hump" at around 100 kHz for the COEO with 2 km loop is the result of the sidemodes. We also measured the phase noise of the COEO at 10 kHz away from the 18-GHz carrier as a function of the loop length, and the result is shown in Fig. 9(b). As expected, the phase noise decreases with the loop length. However, the rate of the decrease is smaller than expected 20 dB/decade[2]. This may be due to the low optical power of the laser and the relatively high spontaneous emission noise from the EDFA. Nevertheless, the phase noise of the first

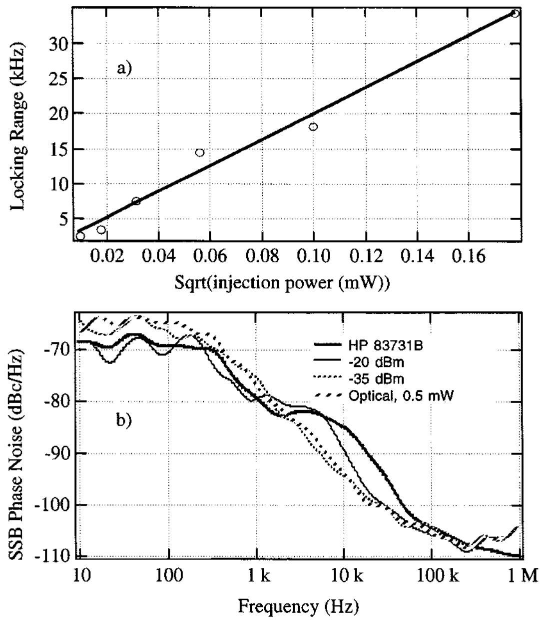

Fig. 10. Experimental results of an injection locked COEO. (a) Locking range as a function of the square root of the injection power. Circle: experimental data. The injection powers for each data point are: –45, –40, –35, –30, –25, and –20 dBm, respectively. Line: curve fit. (b) SSB phase noise of the COEO under optical injection or RF injection with different injection powers. The SSB phase noise of an HP83731B synthesizer at 18.2 GHz is also shown for comparison.

CPM based COEO at 18 GHz is already at the level of a sophisticated high performance commercial synthesizer.

For system applications, the ability of phase locking the oscillator to a system reference is important. Therefore, we demonstrated both electrical injection locking and remote optical injection locking of the CPM based COEO to a reference source, the HP 83731B synthesizer. As shown in Fig. 7, for electrical injection locking the RF reference is injected directly into the COEO before the RF amplifier via a 3-dB RF coupler. We observed that when the injection frequency was within the injection locking bandwidth (determined by the injection power), the frequency of the COEO immediately locked to that of the reference and followed the change of the reference. Fig. 10(a) shows the measured injection locking range as a function of the square root of the injection power, while Fig. 10(b) shows the phase noise of the injection locked COEO. As can be seem from Fig. 10(b), the low phase noise characteristics of the COEO at around 10 kHz is preserved while its close-in phase noise around 10 Hz to 1 kHz follows that of the injection source.

An added advantage of the COEO is that it can be optically injection-locked to a remote reference via an optical fiber link. As indicated in Fig. 7, a reference source with a frequency at around 18.2 GHz and a power of 20 dBm first modulated an optical carrier at around 1319 nm via a MZ modulator. The modulated optical carrier with a power of 0.5 mW was then injected into the COEO at the 3-dB optical coupler after traveling 13 km in an optical fiber spool. Just as in the case of electrical injection locking, the COEO immediately was locked to the frequency of the reference. The phase noise of the optically injection-locked COEO is also shown in Fig. 10(b).

IV. Summary

Two new types of coupled optoelectronic oscillators were investigated experimentally. We generated 15 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 simultaneous generation of a 18.2 GHz RF signal and a pulse train having a pulsewidth of 6.2 ps and a repetition rate of 18.2 GHz with a COEO based on colliding pulse mode-locked (CPM) lasers. Such COEO's can be used as either a compact stand-alone (no RF synthesizer required) optical pulse source, or a RF source with a frequency jitter (or phase noise) equal to or better than a high performance synthesizer. We also demonstrated phase locking the COEO either with a local RF reference electronically or with a remote RF reference optically. We anticipate that the phase noise and jitter of a COEO will reach those of an OEO (phase noise of −140 dBc/Hz @ 10 kHz away from a 10 GHz carrier) in the near future.

Acknowledgment

The authors would like to 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. Lett.*, vol. 21, no. 7, pp. 483–485, 1996.

[2] ——, "Optoelectronic microwave oscillator," *J. Opt. Soc. Amer. B*, vol. 13, no. 8, pp. 1725–1735, 1996.

[3] ——, "Ultra-low phase noise dual-loop optoelectronic oscillator," in *Proc. OFC'98 Tech. Dig.*, 1998, pp. 353–354.

[4] ——, "Dual microwave and optical oscillator," *Opt. Lett.*, vol. 22, no. 24, pp. 1867–1869, 1997.

[5] M. Nakazawa, E. Yoshida, and Y. Kimura, "Ultrastable harmonically and regeneratively modelocked polarization-maintaining erbium fiber laser," *Electron. Lett.*, vol. 30, no. 19, pp. 1603–1605, 1994.

[6] G. R. Huggett, "Mode-locking of CW lasers by regenrative RF feedback," *Appl. Phys. Lett.*, vol. 13, no. 5, pp. 186–187, 1968.

[7] J. D. Kafka, M. L. Watts, and J. J. Pieterse, "Picosecond and femtosecond pulse generation in a regeneratively mode-locked Ti : Sapphire laser," *IEEE J. Quantum Electron.*, vol. 28, no. 10, pp. 2151–2161, 1992.

[8] Y. K. Chen and M. Wu, "Monolithic colliding-pulse mode-locked quantum well lasers," *IEEE J. Quantum Electron.*, vol. 28, no. 10, pp. 2176–2185, 1992.

[9] L. Davis, M. G. Young, D. Doughterty, S. Keo, R. Muller, and P. Maker, "Multi-wavelength mode-locked laser arrays for WDM applications," *Electron. Lett.* , vol. 34, no. 19, pp. 1858–1860, 1998.

[10] L. Davis, M. G. Young, D. Doughterty, and S. Forrouhar, "Wavelength control in mode-locked lasers for WDM applications," in *Proc. SPIE Photon. West*, San Jose, CA, Jan. 1998.

X. Steve Yao, photograph and biography not available at the time of publication.

Larry Davis, photograph and biography not available at the time of publication.

Lute Maleki, photograph and biography not available at the time of publication.