Dual microwave and optical oscillator

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We describe and demonstrate a novel device in which a microwave oscillation and an optical oscillation are generated and directly coupled with each other. With the mutual influence between the microwave and the optical oscillations, we project that this device is capable of simultaneously generating stable optical pulses down to the subpicosecond level and spectrally pure microwave signals at frequencies greater than 70 GHz.

In a series of previous papers we demonstrated an optoelectronic oscillator (OEO) with high stability, high spectral purity, high frequency, and the features of both optical and electrical outputs.[1,2] Such an oscillator is attractive for rf and microwave photonic applications, fiber-optic communications, and high-speed photonic analog–digital conversion.

In this Letter we introduce a novel device based on the OEO architecture that simultaneously produces rf reference signals and stable, short optical pulses. Unlike in the original OEO,[1] in which the laser oscillation is isolated from the optoelectronic oscillation, in this new device the optical oscillation is coupled with the optoelectrical oscillation, and therefore the generated rf and optical signals have fixed phase relations. Although this coupled optoelectronic oscillator (COEO) is similar to the regenerative mode-locked laser[3–7] and the actively mode-locked laser,[8] there are several important differences. In the discussion below, we describe the basis of the COEO, present data on the first demonstration of such a device in our laboratory, and point out features that are distinct from those of other mode-locking schemes.

The basis of the COEO is similar to that of the OEO in that light from a laser source is used in an electro-optic feedback loop for generation of microwave oscillation. However, unlike in the OEO, here the microwave oscillation is fed back to the light source and influences the optical radiation. To demonstrate this scheme we first constructed a ring laser with a custom–made semiconductor optical amplifier (SOA). The amplifier has a small-signal gain of ~15 dB, peaked at 1298 nm, and a built-in optical isolator with an isolation of 30 dB. A rf port built into the SOA permits gain modulation of the amplifier. To construct the ring laser, we used a 3-dB optical coupler with an excess loss of 0.5 dB. The final ring laser construction is shown in Fig. 1(a), and the measured power versus drive-current curve is shown in Fig. 1(b). It can be seen that the ring laser has a threshold of 50 mA and a slope efficiency of 0.16 W/A. The output power of this device reached 15 mW with a drive current of 253.6 mA. The ring laser has many longitudinal modes with a mode spacing determined by the loop (cavity) length of the ring. The measured mode spacing was 23.3 MHz, corresponding to a loop length of 8.58 m.

With this ring laser we constructed a COEO, as shown in Fig. 2(a). The output of the ring laser (from port 3 of the coupler) is connected to a second coupler with a coupling ratio of 10%. Roughly 90% of the light from the ring laser is detected by a photodetector and amplified by a rf amplifier. The amplified signal then goes through a variable delay line, a rf bandpass filter, a rf variable attenuator, and finally a coupler before it is fed back to the rf modulation port of the SOA to form an optoelectronic feedback loop. As with an OEO, when the gain of the feedback loop is larger than 1, an electro-optic oscillation will start.[1,2] The rf variable delay line is used for adjustment of the loop length, and the variable attenuator is used for adjustment of the loop gain. We use the rf coupler to pick out the oscillation signal.

The optoelectronic feedback loop (~100 m in the experiment) is much longer than the loop length of the ring laser, resulting in a corresponding mode spacing much smaller than the mode spacing of the ring laser, as shown in Figs. 2(b) and 2(d). The center frequency of the rf bandpass filter is chosen such that it is equal to a beat frequency of a set of modes of the ring laser, as shown in Fig. 2(c). The bandwidth of the filter is chosen to be narrower than the spacing of the beat frequencies (equivalent to the mode spacing of the ring laser). Within the passband there are many OEO modes that are competing to oscillate. The winner is the mode with a frequency that is closest to a beat frequency of the laser's longitudinal modes, since only this mode can obtain energy from the laser, as shown in Fig. 2(d). This OEO mode is fed back for modulation of the gain of the ring laser and effectively mode locks the ring laser. The mode locking makes

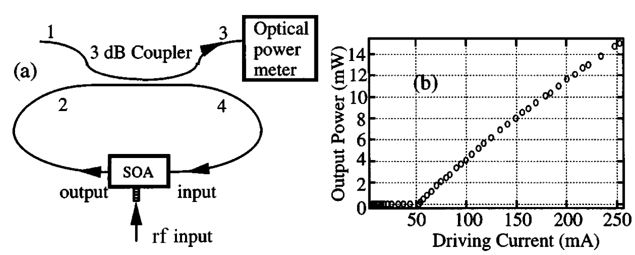

Fig. 1. (a) Ring laser built with a semiconductor optical amplifier: 1–4, ports of the optical coupler. (b) Measured power versus drive-current curve of the ring laser.

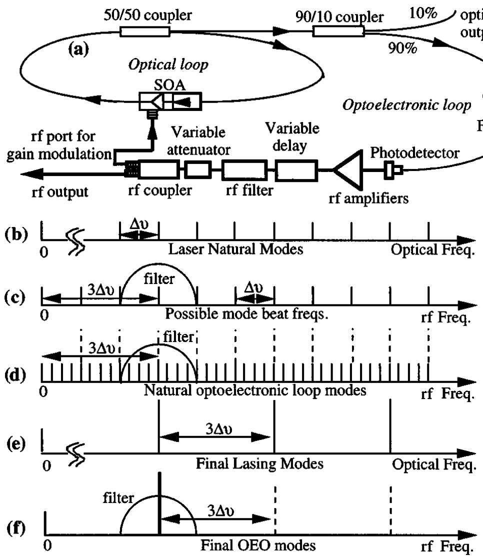

Fig. 2. (a) Schematic of a COEO. (b) All possible laser modes with a mode spacing of $\Delta\nu$. The modes have random phases in the absence of the electro-optic feedback. (c) All possible mode beat frequencies of the laser modes in the photodetector. The lowest frequency ($\Delta\nu$) corresponds to the sum of the beats between adjacent modes; the second lowest frequency ($2\Delta\nu$), to the sum of the beats between every other mode; and so on. Owing 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 that are aligned with a mode beat frequency can obtain 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 figure) 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 laser equal to the frequency of the oscillating OEO mode, which is multiple of the natural mode spacing of the laser, as shown in Fig. 2(e). Because all the oscillating modes in the mode-locked laser are forced into phase, all the mode beat signals between any two neighboring laser modes will add 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. 2(f).

This configuration is effectively a double-loop OEO,[9] except that here the second loop is a pure optical cavity and an integral part of the pump laser. However, from the outside this double-loop OEO is just like a single-loop OEO without any extra components. Because the optical cavity can be made sufficiently short, the laser mode spacing can be made much larger than is possible with an optoelectronic loop. The larger mode spacing ensures a large frequency tunability for the COEO and may result in the elimination of the bulky rf filter used in an ordinary OEO.

In the first experiment a bandpass filter centered at 300 MHz with a bandwidth of 13 MHz was used in the optoelectronic loop. The mode beat spectrum of the mode-locked laser, shown in Fig. 3(a), was measured at the optical output port of the COEO by a photodetector with a bandwidth of 18 GHz and a Hewlett–Packard 8562A spectrum analyzer. The peaks of the rf spectrum result from the beat between the longitudinal modes in the ring laser. The lowest frequency corresponds to the beat between any two neighboring modes; the second lowest frequency, to the beat between every other mode; and so on. It can be inferred from the spectrum that ~20 modes of the ring laser were mode locked. Figure 3(b) shows the rf spectrum of the oscillation signal measured at the rf output port. A clean signal at 288 MHz with a power of −30 dBm is evident. When we take the −35-dB coupling ratio of the rf coupler into account, the rf signal circulating in the loop is ~5 dBm, which is limited by the rf amplifier used. The ring laser, as expected, was also automatically mode locked by this self-generated rf signal for production of a train of short optical pulses, as shown in Fig. 3(c). The pulse width is ~250 ps, and the periodicity of the pulses is ~3.6 ns. The time-domain data were taken with a HP CSA803 communication signal analyzer.

In another experiment we used a filter centered at 800 MHz with a bandwidth of 40 MHz to replace the 300-MHz filter. Here the COEO oscillates at ~800 MHz and the oscillating rf signal mode locks the ring laser. The rf spectrum of the COEO is shown in Fig. 4(a). It is evident from Fig. 4(a) that a signal with high spectral purity was obtained with the COEO. The corresponding pulse train of the mode-locked ring laser, shown in Fig. 4(b), has a pulse width of ~50 ps and a pulse train with an ~1.2-ns period. As expected the pulse width is greatly shortened with the increase of the oscillation frequency. Although

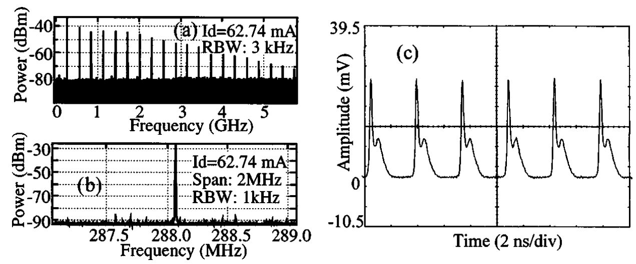

Fig. 3. COEO with a 300-MHz filter. (a) Mode beat spectrum of the COEO measured at the optical output port. (b) rf spectrum of the COEO measured at the electrical output port. (c) Time-domain measurements of the COEO at the optical output port. I_d, laser drive current; RBW, resolution bandwidth setting of the spectrum analyzer.

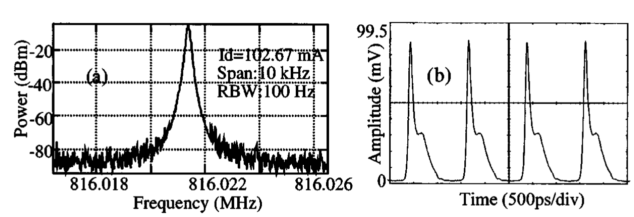

Fig. 4. COEO with an 800-MHz filter. (a) rf spectrum of the COEO at the rf output port. (b) Time-domain measurement of the COEO at the optical output port. A train of 50-ps short pulses is evident.

much shorter pulses can be obtained with increased COEO oscillation frequency, we were unfortunately limited by the slow response of the SOA that resulted from nonoptimized packaging. By using a fast amplitude or phase modulator inside the optical loop, we expect to increase greatly the oscillation frequency (to 70 GHz; the frequency will be limited only by the speed of the modulator) while decreasing the pulse width. Other types of laser, such as an Er^+-doped-fiber laser, can also be used for construction of a COEO in this fashion. We also anticipate that by using a multimode diode laser with a simple Fabry–Perot cavity directly we can construct a very compact and efficient COEO to generate a stable high-frequency rf oscillation and a train of stable high-repetition-rate subpicosecond optical pulses simultaneously.

Note that because of the self-correcting mechanism[9] of the coupled oscillation the mode-locked laser output and the microwave output were both very stable.[10] As in an ordinary OEO,[1] we expect further improved stability and spectral purity of the optoelectronic oscillation with an increased optoelectronic loop length (a few kilometers), which will in turn make the laser pulses more stable.

The COEO is clearly different from active mode-locked lasers in that it operates without an external rf source. Although the hardware arrangement of the regenerative mode locking[3–7] resembles that of the COEO, there are the following distinct differences between the two: First, unlike in a COEO, in the regenerative mode-locking scheme the optoelectronic feedback loop does not need to oscillate (i.e., the open-loop gain of the optoelectronic feedback does not need to exceed unity), and so the laser is merely driven by an amplified beat signal. As a result the modes in the optoelectronic loop were not considered in the previous discussion of regenerative mode-locking schemes.[3–7] On the other hand, in a COEO the optoelectronic loop is required to oscillate, and the modes in the optoelectronic loop are coupled with the laser modes in the same fashion as in two coupled oscillators. Consequently the stability of the OEO oscillation will influence the laser oscillation and vice versa. Second, the previous studies[3–7] of regenerative mode locking concentrated merely on making lasers for mode locking; here we emphasize generation of low-phase-noise microwave signals and low-jitter optical pulses simultaneously, which adds a new dimension beyond regenerative mode locking. Third, based on the theoretical analysis and experimental results of our study of the original OEO,[1] we require the optoelectronic loop of a COEO to be quite long for generation of low-phase-noise rf signals. On the other hand, there is no loop-length requirement in the regenerative mode-locking setups. Fourth, with a long optoelectronic loop, the mode spacing of the optoelectronic oscillation becomes small, so the interaction of the optical oscillation and the optoelectronic oscillation becomes extremely important for single-opto-electronic mode selection. However, in previous studies of regenerative mode locking, such interaction and single-optoelectronic-mode selection were not observed or considered. Finally, here we emphasize the importance of mode coupling between the laser modes and the modes in the optoelectronic loop and qualitatively analyze their interactions in a COEO. Because the device essentially comprises a coupled pair of rf and optical oscillators, the rf signal can be injection locked or phase locked to a rf standard for further stabilization or synchronization of both signals.

In summary, we have demonstrated a coupled optoelectronic oscillator in which the laser oscillation is directly coupled with the electronic oscillation. Such a coupled oscillator easily accomplishes single-mode selection even with a sufficiently long optoelectronic feedback loop, a task that is difficult to accomplish in an ordinary OEO. In addition, in a COEO a multimode laser is used to pump the electronic oscillation. The coupling of the microwave oscillation with the laser causes the laser to mode lock, generating stable optical pulses and microwave signals simultaneously. An important feature of our study is that we used a solid-state optical amplifier to demonstrate the COEO. We anticipate, however, that the concept of the COEO can be applied to any type of laser system, including Er^+-doped-fiber, solid-state, diode, and gas-laser systems, for generation of stable optical pulses down to the subpicosecond level and high-frequency rf signals greater than 70 GHz (limited by the speed of the external modulators).

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