A Dual-Loop Opto-Electronic Oscillator

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We describe and demonstrate a multiloop technique for single-mode selection in an opto-electronic oscillator (OEO). We present experimental results of a dual-loop OEO free running at 10 GHz that has the lowest phase noise (–140 dBc/Hz at 10 kHz from the carrier) of all free-running room-temperature oscillators to date.

I. Introduction

Opto-electronic oscillators (OEOs) [1–3] have many attractive properties [4] for microwave photonic communication systems, radar systems, and fiber-optic communication systems. These properties include high spectral purity, high frequency generation capability, tunability, dual electrical and optical interfacing capability, and dual optical and electrical output capability.

The OEO consists of a pump laser and a feedback circuit including an electro-optic amplitude modulator, an optical fiber delay line, a photodetector, an electrical amplifier, and an electrical bandpass filter. Its oscillation frequency, limited only by the speed of the modulator and photodetector, can be up to 100 GHz.

In general, many modes can oscillate in an OEO. Single-mode operation of the oscillator is established by including an RF filter in the loop to allow only one mode to oscillate while suppressing other oscillation modes. Both our theoretical and our experimental studies indicate that the phase noise of the oscillator decreases quadratically with the loop-delay time. Therefore, increasing the OEO loop length is an effective way of reducing the oscillator's phase noise. Unfortunately, for a sufficiently long loop, it is impossible to find an RF filter that is narrow enough to sustain single-mode operation, because the mode spacing is the inverse of the delay time of the feedback loop. For example, for a loop length of 1 km, the mode spacing is 200 kHz and the filter bandwidth has to be on the order of a few hundred kilohertz. Such a narrow bandwidth is extremely difficult to obtain for a filter centered at 10 GHz. In addition, the inclusion of a narrow filter in the loop sacrifices the oscillator's tunability.

We present here a multiloop technique that permits the OEO to operate in a single mode while having a long loop length, resulting in a reduced phase noise. It relaxes the requirement of bandwidth or eliminates the need for an RF filter in the loop, making the oscillator widely tunable. Furthermore, it reduces the oscillation threshold of the OEO by as much as 6 dB, reducing the gain requirement of the RF amplifier.

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II. Analysis

To illustrate the operation principle of the multiloop technique, a double-loop OEO is shown in Fig. 1. Unlike a single-loop OEO, which only has one feedback loop, in a double-loop OEO, there are two feedback loops of different lengths. The open-loop gain of each loop may be less than unity; however, the combined open-loop gain of both loops is larger than unity. For a double-loop OEO, the possible oscillation frequencies must add up in phase after each round-trip around both loops:

$$f_{osc} = \frac{k + \frac{1}{2}}{\tau_1} = \frac{m + \frac{1}{2}}{\tau_2} \tag{1a}$$

for $G(V_{osc}) < 0$ and

$$f_{osc} = \frac{k}{\tau_1} = \frac{m}{\tau_2} \tag{1b}$$

for $G(V_{osc}) > 0$, where k and m are integers, $G(V_{osc})$ is the open-loop voltage gain, and τ_1 and τ_2 are the loop delays of loop 1 and loop 2, respectively. From Eqs. (1a) and (1b), one can see that if loop 2 is n times shorter than loop 1 ($\tau_1 = n\tau_2$), then n must be an odd integer for the case that $G(V_{osc}) < 0$ and an integer (even and odd) for the case that $G(V_{osc}) > 0$. The mode spacing is then dictated by the shorter loop: $\Delta f = 1/\tau_2$. On the other hand, the phase noise of the oscillator is dictated by the longer loop, resulting in an oscillator having large mode spacing and low phase noise.

The RF spectrum of the double-loop OEO can be analyzed using the same quasilinear theory developed for the single-loop OEO [1]. Similarly to the single-loop OEO, the recursive relation for the double-loop oscillator can be expressed as

$$\tilde{V}_j(\omega) = \left(g_1 e^{i\omega\tau_1} + g_2 e^{i\omega\tau_2}\right) \tilde{V}_{j-1}(\omega) \tag{2}$$

where $\tilde{V}_j(\omega)$ is the complex amplitude of the circulating field after a round-trip, g_1 is the complex gain of loop 1, and g_2 is the complex gain of loop 2. The total field of all circulating fields is thus

$$\tilde{V}_{\text{out}}(\omega) = \sum_{j=0}^{\infty} \left(g_1 e^{i\omega\tau_1} + g_2 e^{i\omega\tau_2}\right)^j \tilde{V}_j(\omega) = \frac{\tilde{V}_o}{1 - \left(g_1 e^{i\omega\tau_1} + g_2 e^{i\omega\tau_2}\right)} \tag{3}$$

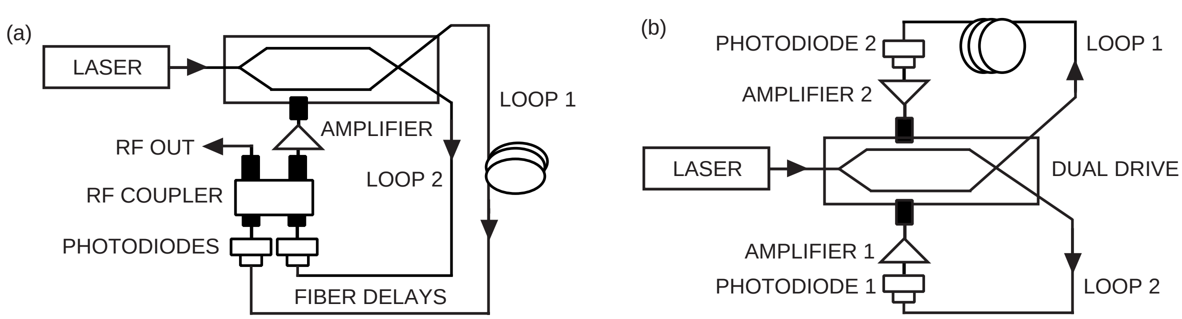

Fig. 1. Two examples of configurations of a double-loop OEO: (a) a dual-loop OEO with a single RF drive modulator and (b) a dual-loop OEO with a dual RF drive modulator.

The corresponding RF power, $P(\omega) \equiv |\tilde{V}_{out}(\omega)|^2/2R$, therefore, is

$$P(\omega) = \frac{\frac{|V_o|^2}{2R}}{1 + |g_1|^2 + |g_2|^2 + 2|g_1||g_2|\cos(\Phi_1 - \Phi_2) - 2(|g_1|\cos\Phi_1 + |g_1|\cos\Phi_1)} \tag{4}$$

where

$$\Phi_i(\omega) = \omega\tau_i + \phi_i \qquad i = 1, 2 \tag{5}$$

In Eq. (5), ϕ_i is the phase factor of the complex gain g_i.

If the gain of each loop is less than unity, no oscillation may start independently in either loop. However, for the frequency components satisfying Eq. (1), oscillation can start collectively in the two loops. When Eq. (1) is satisfied, we have

$$\Phi_1(\omega) = 2k\pi \tag{6a}$$

$$\Phi_2(\omega) = 2m\pi \tag{6b}$$

$$\Phi_1(\omega) - \Phi_2(\omega) = 2(k - m)\pi \tag{6c}$$

Substituting Eq. (6) in Eq. (4) yields

$$P(\omega) = \frac{\frac{|V_o|^2}{2R}}{1 + |g_1|^2 + |g_2|^2 + 2|g_1||g_2| - 2|g_1| - 2|g_1|} \tag{7}$$

In order for the oscillation to start from noise, we must have

$$1 + |g_1|^2 + |g_2|^2 + 2|g_1||g_2| - 2|g_1| - 2|g_1| = 0 \tag{8}$$

For $|g_1| = |g_2|$, we obtain

$$|g_1| = |g_2| = 0.5 \tag{9}$$

This is the oscillation threshold for the double-loop OEO. If initially the small signal gain in each loop is larger than 0.5, the nonlinearity of the electro-optic (E/O) modulator or the amplifier will bring the gain to 0.5 after the oscillation is started and stabilized.

Figure 2 shows the calculated frequency spectrum of the double-loop OEO from Eq. (7). In the calculation, we chose $|g_1| = |g_2| = 0.5 - 10^{-8}$, $|V_o|^2/2R = 1$, $\tau_1 = 0.1$ μs, and $\tau_2 = 10\tau_1 = 1$ μs. Figure 2(a) shows the spectrum of an OEO of loop 2 alone; Fig. 2(b) is the spectrum of loop 1 alone; and Fig. 2(c) is the spectrum of the OEO with both loops present. The relative power of the vertical axis is the calculated power of each case divided by the calculated peak power of the double-loop OEO. Note that the relative power for Figs. 2(a) and 2(c) are extremely low, due to the fact that the loop gain is too

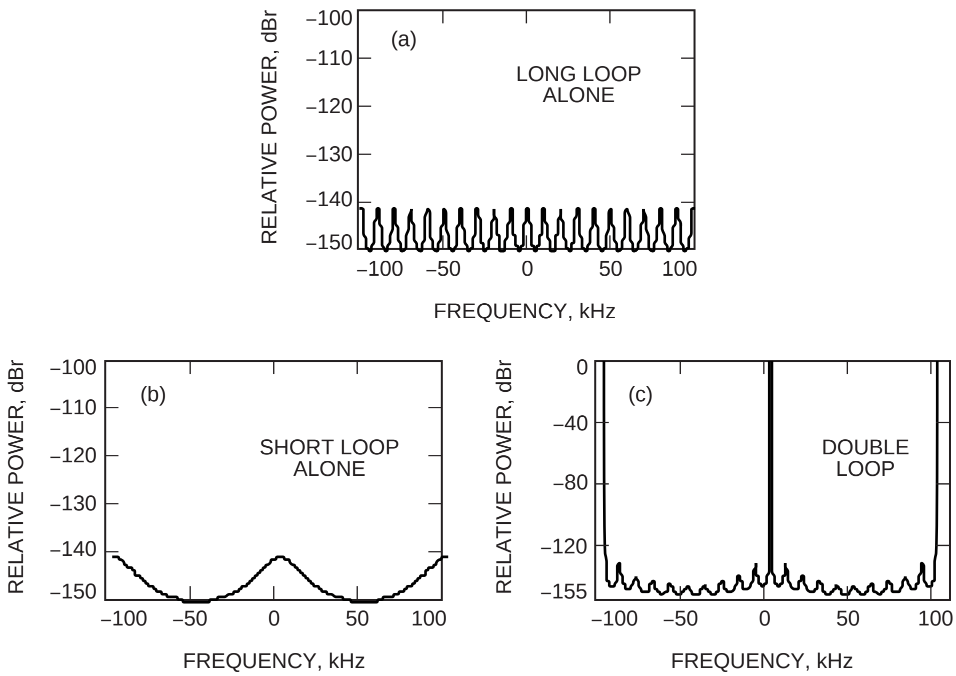

Fig. 2. Calculated spectra of the double-loop OEO: (a) loop 2 alone, (b) loop 1 alone, and (c) both loops present.

small for each loop to oscillate individually. For the double-loop case of Fig. 2(c), a strong oscillation at selected frequencies is evident, with the mode spacing determined by the shorter loop and the spectral width determined by the long loop, which agreed with our expectation.

Because of the relatively large mode spacing, single-mode operation of the OEO can easily be achieved by including a filter of relatively wide bandwidth. Because $\Delta f/f = -\Delta L/L$, where f is the oscillation frequency, L is the loop length, and Δf is the frequency change caused by the loop length change ΔL, the oscillation frequency of the double-loop OEO can be more sensitively tuned by changing the loop length of the shorter loop. The tuning range is determined by the mode spacing of the shorter loop, and the tuning resolution is determined by the mode spacing of the longer loop. For example, if the short loop is 20 cm and the long loop is 10 km, the tuning range will be 1 GHz and the tuning resolution will be 20 kHz. In practice, due to the mode-pulling effect, the tuning is rather continuous before hopping to a different mode of the long loop.

For a larger tuning range, a tunable RF filter can be used. However, the tuning of the center frequency of the filter should be synchronized with the tuning of the loop length, which tunes the oscillation frequency of the OEO. The combination of the double-loop OEO and the tunable RF filter produces a novel frequency synthesizer with a wide frequency-tuning range (tens of gigahertz), low phase noise, and high frequency resolution.

III. Experiment

The double-loop configuration depicted in Fig. 1(b) was used in the experimental setup. In the experiment, a dual-drive electro-optic modulator was used. The shorter loop included a photodetector and an RF amplifier. The longer loop ($\sim$1 km in length) included another photodetector, a filter centered at 5 GHz, and another RF amplifier. Figure 3(a) shows the multimode oscillation of a single-loop OEO in which the shorter loop is disconnected; however, the longer loop is closed and its open-loop gain is larger than unity. Figure 3(b) shows the single-mode oscillation of a double-loop OEO in which both

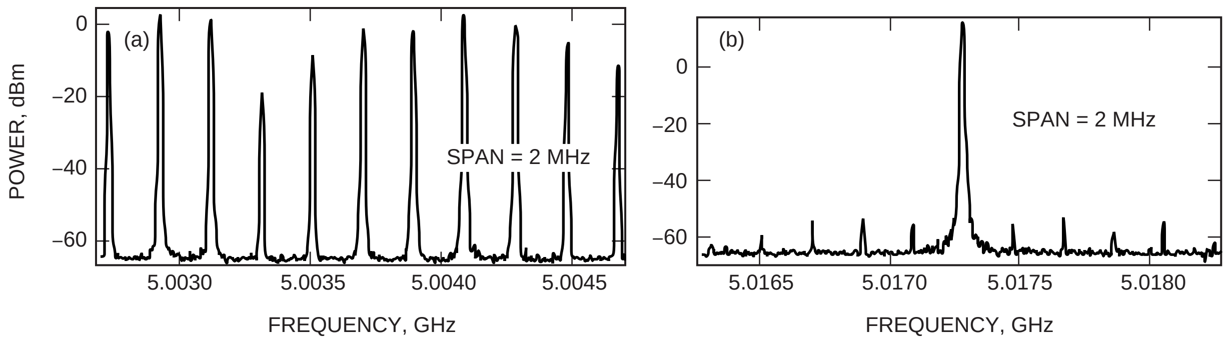

Fig. 3. Experimental results showing the effectiveness of the double-loop mode-selection technique: (a) multi-mode oscillation of a single-loop OEO and (b) single-mode oscillation of a double-loop OEO. In both cases, the resolution bandwidth (RBW) of the spectrum analyzer was set at 3 kHz.

loops are closed and the gain of each loop was adjusted by inserting attenuators of proper values so that it was below the oscillation threshold. However, the combined loop gain for a particular mode was larger than unity. It is evident that the presence of the shorter loop effectively suppresses other modes of the longer loop and only leaves one mode to oscillate. The mode-suppression ratio is more than 60 dB. We find that even when the gain of each loop is larger than unity (each loop may oscillate by itself), the dual-loop configuration still is effective in single-mode selection. The side-mode suppression ratio of more than 70 dB has been achieved.

It should be noted that an added advantage of the double-loop configuration is that, for a fixed optical pump power, the second loop increases the open-loop gain by 6 dB and, hence, lowers the oscillation threshold by 6 dB, making it easier to realize an OEO without employing an RF amplifier.

We constructed another dual-loop OEO with 2-km thermally stabilized fiber in the long loop and a filter centered at 10 GHz with a bandwidth of 40 MHz in each loop, as shown in Fig. 4. The spectra of the OEO output are shown in Fig. 5 and are compared with the spectra of a Hewlett Packard (HP) high-performance RF synthesizer (Model 8617B) for different spectrum analyzer settings. It is evident that the spectrum purity of the OEO is significantly better than that of the HP synthesizer for this purpose.

We used the frequency discrimination method to measure the phase noise of the double-loop OEO, and the experimental setup is shown in Fig. 4. In the setup, the reference fiber has a length of 12.8 km, significantly longer than the longer loop of the OEO. Both the loop fiber and the reference fiber are

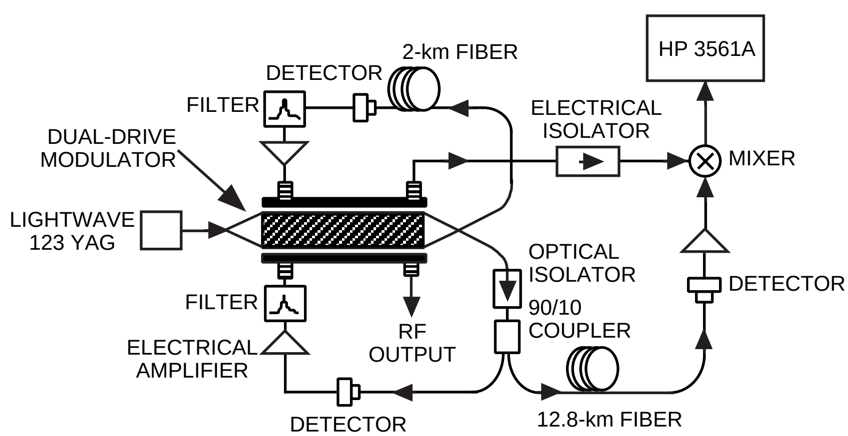

Fig. 4. Frequency discriminator setup for measuring the phase noise of the dual-loop OEO.

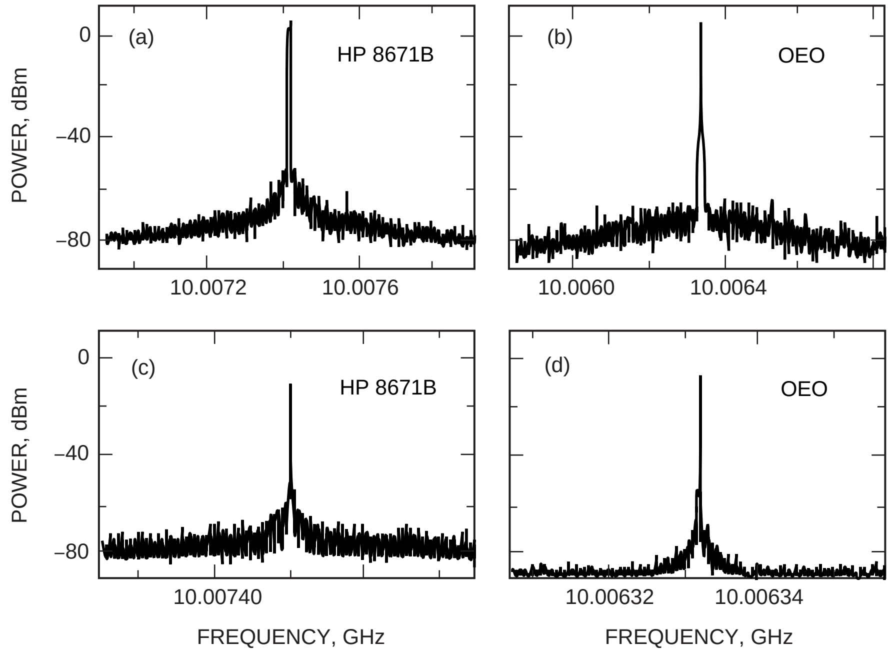

Fig. 5. A comparison of the spectral purity of a double-loop OEO and an HP 8671B synthesizer at different spectrum analyzer settings: (a) HP 8671B at 1-MHz span and 1-kHz RBW, (b) OEO at 1-MHz span and 1-kHz RBW, (c) HP 8671B at 50-kHz span and 10-Hz RBW, and (d) OEO at 50-kHz span and 10-Hz RBW.

acoustically isolated in a box padded with lead-backed foam. Figure 6 shows the measured phase noise as a function of offset frequency. It should be noted that at 10 kHz from the carrier (10 GHz), the phase noise of the double-loop OEO is -140 dBc/Hz. As a comparison, we measured the phase noise of the high-performance HP frequency synthesizer (HP 8617B) using the same measurement setup as that shown in Fig. 4, however disconnecting the 2-km loop of the OEO at the RF input port to the modulator and then connecting the output of the frequency synthesizer to the RF input port. The result indicates that the synthesizer's phase noise at 10 kHz away from the 10-GHz carrier is about -96 dBc/Hz, more than 40 dB higher than that of the double-loop OEO. By comparing the phase noise of the OEO with that of a free-running sapphire-loaded cavity (SLC) oscillator [5], it is evident that the phase noise of the OEO is significantly lower than that of the SLC oscillator.

Figure 6 also shows that the slope of the phase noise of the OEO as a function of the frequency offset is 30 dB/decade, about 10-dB/decade higher than predicted [2]. This is an indication that a $1/f$ noise source is present in the loop and has to be removed for better noise performance. This $1/f$ noise may come from the RF amplifiers used in the loop and can be removed with a carrier suppression technique [5,6].

Finally, the Allan variance of the OEO was measured to be 10^{-10} at 1 second, which is consistent with that calculated from the measured phase noise at 1 Hz. We expect improved Allan variance performance by reducing the close-in phase noise and stabilizing the temperature of the OEO.

We estimate that the ultimate stability of the OEO is on the order of 10^{-14}. This estimation is based on our experimental investigation of the low thermal coefficient of delay (TCD) fiber commercially available. As shown in Fig. 7, this fiber has a zero TCD around a few degrees centigrade. Curve fitting the experimental data yields

$$TCD = -1.5 \times 1^{-8}(T - T_o) \tag{10}$$

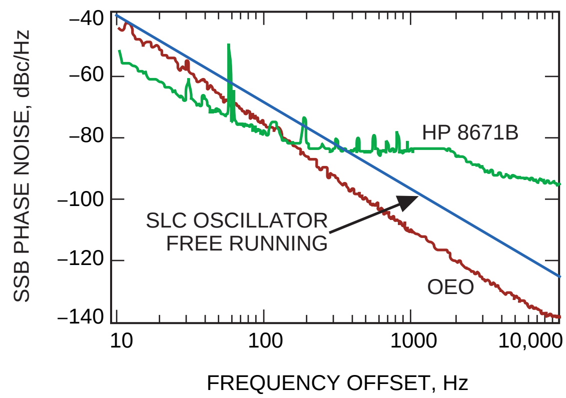

Fig. 6. A comparison of single side-band (SSB) phase noise of the OEO and other oscillators.

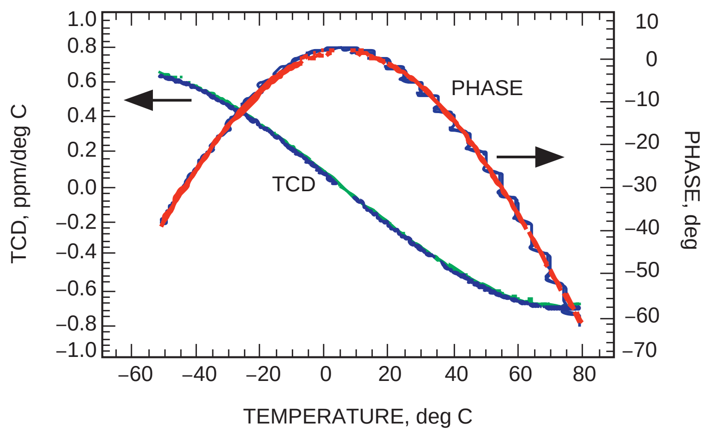

Fig. 7. Temperature dependencies of the thermal coefficient of delay of the low TCD fiber and the RF phase of a 0.5-GHz signal transmitting through the fiber.

where T is the fiber temperature and T_o is the temperature at which the TCD is zero. On the other hand, the frequency stability of the OEO determined by the temperature fluctuation can be expressed as

$$\frac{\Delta f_{osc}}{f_{osc}} = -\Delta T \times TCD \tag{11}$$

Therefore, one may obtain a frequency stability of 10^{-14} if the fiber is stabilized to within 1 millidegree centigrade from T_o.

We also designed and built a temperature chamber and demonstrated the feasibility of stabilizing a 2-km fiber spool to within 1 millidegree centigrade.

IV. Summary

In summary, we have designed, built, and characterized a double-loop OEO operating at 10 GHz. The free-running OEO has achieved an unsurpassed low phase noise of −140 dBc/Hz at 10 kHz away from the carrier. Such a low phase noise oscillator can find wide applications in radar systems, microwave photonic systems, fiber-optic communications systems, and high-speed analog-to-digital conversion systems. The present frequency stability of the OEO is 10^{-10} at 1 second. We anticipate, based on the temperature stability of the low TCD fiber, that an ultimate frequency stability of 10^{-14} can be achieved with this OEO technology.

Acknowledgments

We thank B. Diener for his help in our Allan variance measurement and J. Dick for helpful discussions.

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