Low-noise RF-amplifier-free slab-coupled optical waveguide coupled optoelectronic oscillators: physics and operation

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Abstract: We demonstrate a 10-GHz RF-amplifier-free slab-coupled optical waveguide coupled optoelectronic oscillator (SCOW-COEO) system operating with low phase-noise (<-115 dBc/Hz at 1 kHz offset) and large sidemode suppression (>70 dB measurement-limited). The optical pulses generated by the SCOW-COEO exhibit 26.8-ps pulse width (post compression) with a corresponding spectral bandwidth of 0.25 nm (1.8X transform-limited). We also investigate the mechanisms that limit the performance of the COEO. Our measurements indicate that degradation in the quality factor (Q) of the optical cavity significantly impacts COEO phase-noise through increases in the optical amplifier relative intensity noise (RIN).

OCIS codes: (140.0140) Lasers and laser optics; (250.0250) Optoelectronics.

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1. Introduction

The coupled optoelectronic oscillator (COEO) [1] is a system based on the regenerative modelocked laser (RML) architecture [2, 3] that is capable of generating both an optical pulse train and a low phase-noise microwave tone. The conversion from optical to microwave occurs through the beating of adjacent comb-lines during photodetection. With a long optical delay (~100–300 m), and thus large cavity quality factor (Q), the phase-noise of the generated signal can be lower than that achieved by traditional electronic microwave oscillators [4].

Previous work on COEOs using semiconductor optical gain have shown excellent phase-noise of −115 dBc/Hz at 1-kHz offset frequency operating at a carrier of 10 GHz [5]. Although the pulsewidths were not directly reported in Ref [5], later reports revealed the COEO pulses to be highly asymmetric with widths of 22 ps [6]. Reported COEOs using erbium-doped fiber amplifier (EDFA) gain have also achieved low phase-noise (<-115 dBc/Hz at 1 kHz) and narrow pulsewidth (2 ps) at an oscillation frequency of 9.4 GHz [7]. In this paper, we demonstrate a 10 GHz high-performance slab-coupled optical waveguide COEO (SCOW-COEO) comprising a novel high-power, low-noise semiconductor gain medium. Previous SCOW-COEO work has shown the gain medium to be suitable for generation of a stable microwave signal at 10.24 GHz with optical pulsewidths of 17 ps [8]. In this work, we expand on the previous results and show that low phase-noise can be achieved with greatly suppressed sidemode oscillation (>70 dB). Here, we use the term sidemode to refer to the spurious oscillation modes of both the optical and optoelectronic cavities.

In all of the COEO demonstrations to date, RF amplifiers have been used within the cavity in order to sustain optoelectronic oscillation. The RF amplifier adds noise and degrades the system's size, weight, and power (SWaP) performance. In this paper, we describe the operation of an RF-amplifier-free SCOW-COEO oscillating solely on microwave-photonic (MWP) gain. Most of this paper's focus will be on the phase-noise performance of our COEO system. We will also detail our investigation into the noise properties of the COEO. The findings of this study allow us to identify the parameters important for low phase-noise performance. Finally, we conclude with measurements of the RF spectrum and optical pulse train coupled out of the electrical and optical cavities. Comparisons to a similar system operated with RF amplification will also be provided when applicable.

2. SCOW-COEO system and operation

The COEO is a class of oscillators based on a coupled-cavity system whose oscillation is dependent on the interaction between an optical and optoelectronic cavity [1, 9]. A schematic of the RF-amplifier-free SCOW-COEO is illustrated in Fig. 1. The optical cavity

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configuration of the SCOW-COEO resembles that of a modelocked laser with a slab-coupled optical waveguide amplifier (SCOWA) serving as the active gain medium [10, 11]. The SCOWA used in our experiments exhibited saturation output power P_{sat} ~400 mW and small-signal gain G ~30 dB [11]. Most (80%) of the SCOWA's output power is recirculated within the optical cavity of which 1% is later coupled out as useful output. An isolator was used to maintain uni-directional propagation of the optical power. After the isolator, the signal passes through a $LiNbO_3$ intensity modulator (V_π ~3.0 V at 10 GHz) and finally through a 250-m SMF fiber delay line. Due to the large intracavity circulating power (>250 mW average) allowed by the SCOWA, 2 mW optical power can be coupled out with only a 1% output coupler. In the optoelectronic cavity, the amplified and delayed signal from the 20% coupler passes through a 60-m SMF fiber delay and is incident on a photodiode. The 60-m delay is used for stabilization of the cavity and will be explained in more detail later. In our RF-amplifier-free SCOW-COEO, we used a high-power (I_{sat} = 40mA, BW = 14 GHz) variable confinement SCOW photodiode (VC-SCOWPD) for generation of the microwave signal [12]. The signal is first sent through a phase shifter for fine control of the oscillation frequency and then through an RF filter (BW = 10 MHz). The filter sets the oscillation frequency of the COEO and rejects unwanted frequencies beyond its passband. Finally, 10% of the signal is coupled out as useful RF output, while the remainder is fed back into the modulator to induce self-oscillation. Although not explicitly shown, polarization controllers are included before the modulator, SCOWA, and photodiode for optimizing the functionality of polarization-sensitive components.

The system of Fig. 1 is similar to a RML as both systems have identical configurations consisting of similar loop delays [1, 6, 9]. In the literature, it is often cited that the difference between the two systems is related to the purpose of the electronic feedback. In a COEO, the feedback forms a secondary coupled-cavity of the system, while in a RML, the feedback is intended to stabilize the optical cavity against fluctuations. While this is true, it is unclear whether this distinction plays any role during experimental operation of either system.

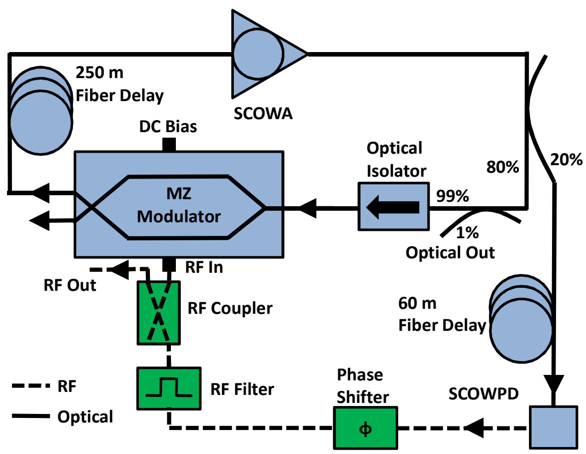

Fig. 1. Schematic of SCOW-COEO system.

From our perspective, the difference between a COEO and a RML appears to be related to the performance metrics that each system is optimized for. A COEO primarily serves the role of a pristine microwave source and is therefore usually optimized for low phase-noise [6]. Historically, the RML has been designed for the generation of high repetition-rate, short-pulse trains where phase-noise was more of a secondary concern [3]. In this paper, we use the terms COEO and RML to be consistent with this definition.

The COEO operates by amplifying noise through successive roundtrips of the cavity until a large steady-state signal is developed. In the first iteration, thermal noise, shot noise, and spontaneous-spontaneous beat noise within the passband of the filter become incident on the

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modulator RF port and induce a small modulation of the amplifier's spontaneous emission. By itself, this process generally undergoes net MWP loss with each roundtrip as the spontaneous emission power is too small to generate a large beat-signal. However, when the optical cavity can also oscillate, the optical power stored within the longitudinal modes can now generate a large microwave signal at the beat frequencies between the cavity modes. If the net MWP gain is larger than unity, the beat frequencies falling within the filter passband induce larger and larger modulation of the optical signal until modelocking occurs. In steady-state, the COEO produces pulses in the optical output and a single low-noise tone through the filtered RF output.

In general, many modes can oscillate within the bandwidth of the RF filter. For example, in our case with ~250 m optical cavity fiber delay, ~12 modes can oscillate within the 10 MHz filter passband. The growth of a single mode and suppression of sidemodes occurs by the Vernier interaction between modes of the optical and optoelectronic cavity [1, 9]. The lengths of these two cavities are slightly offset such that only one set of modes within the filter passband can simultaneously satisfy both resonance conditions. Any frequency that satisfies the resonance of only one cavity will be greatly attenuated through the filter response of the second cavity. As such, large suppression of the sidemodes can be achieved without any additional requirement of complexity or cost. The 60 m of optical fiber in Fig. 1 then was optimized for the purpose of offsetting the resonance frequencies of the optoelectronic cavity from that of the optical cavity.

3. Results and discussion

The results of our SCOW-COEO system are divided into two subsections. The first subsection describes the phase-noise characterization of the oscillator, while the second details the RF spectrum and optical pulse measurements.

3.1 SCOW-COEO phase-noise

We measured the phase-noise of the 10-GHz RF-amplifier-free SCOW-COEO in Fig. 1 using a commercial Agilent E5052B signal-source analyzer (SSA) and E5053A microwave downconverter. Figure 2 shows the results of this measurement along with the phase-noise of a SCOW-COEO constructed using a commercial Discovery Semiconductors DSC50S photodiode. As the commercial photodiode does not provide sufficient current to achieve net MWP gain, a commercial low phase-noise RF amplifier (AML612PNA1211) was used to sustain oscillation. Aside from the photodiode and RF amplifier, both systems are otherwise identical. One-thousand (1000) cross-correlations were used in the measurement to reduce the SSA phase-noise floor (dashed line). The floor was estimated from the frequencies where cross-correlation averaging improves the phase-noise. The operation photocurrent was 36.2 mA using the VC-SCOWPD configuration and 16.1 mA using the DSC50S + RF amplifier configuration. In both cases, the SCOW-COEO is noise-floor limited throughout most of the offset frequency range beyond 15 kHz. For frequencies between 5 and 15 kHz, only the RF-amplifier-free SCOW-COEO remains measurement limited.

The intracavity powers for each system can be calculated from their respective photocurrents. With 36.2 mA of photocurrent on the VC-SCOWPD and 0.7 A/W responsivity (and using a 80:20 coupling ratio), the average intracavity optical power is ~260 mW. However, with 16.1 mA of photocurrent on the DSC50S and 0.8 A/W responsivity, the intracavity optical power decreases to ~100 mW.

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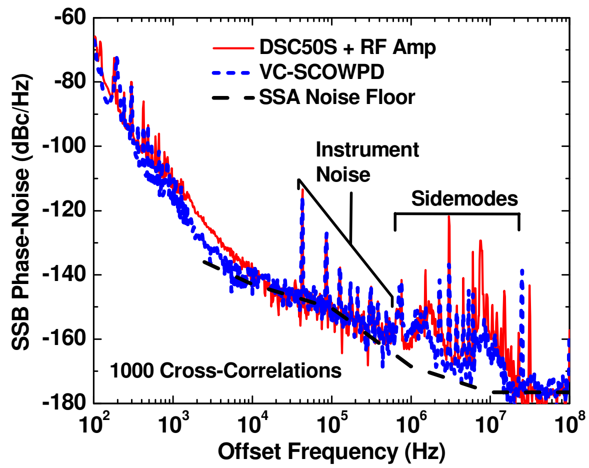

Fig. 2. Measured phase-noise of a VC-SCOWPD SCOW-COEO system (blue dashed-line) and of a DSC50S + RF amplifier SCOW-COEO system (red line). The phase-noise floor (black dashed line) is also provided.

The improvement in phase-noise afforded by using a high-power system is reflected in Fig. 2. The phase-noise is <-115 dBc/Hz and <-110 dBc/Hz at 1 kHz offset for the VC-SCOWPD and DSC50S + RF amplifier systems, respectively. As we will show later, this improvement in phase-noise is due to a decrease in relative intensity noise (RIN) as the circulating power is increased in the optical cavity. Because COEO oscillation starts from intensity fluctuations, the level of RIN directly impacts the phase-noise of the system, similar to the case of an optoelectronic oscillator [13]. One additional disadvantage of the DSC50S system is that it requires the use of RF amplification to achieve the necessary gain to oscillate. Although the RF amplifier phase-noise does not limit the measurement here, ~10 W electrical power is required to maintain its operation. Therefore, removal of the RF amplifier offers significant benefits in SWaP performance.

The sidemodes also improve from <-120 dBc/Hz to <-135 dBc/Hz using the VC-SCOWPD system. Note that the spurs at harmonics of 43 kHz and the spur near 20-30 MHz are introduced by the SSA and microwave downconverter. The reduction of sidemode levels results from increased saturation of the semiconductor gain medium. It is well known that saturation of an optical amplifier suppresses the intensity noise at frequencies below the inverse of the gain medium's carrier lifetime [14]. Above the inverse carrier lifetime, the carriers cannot respond to the intensity fluctuations, and therefore the amplifier completely passes high frequency noise to the output. The beat frequencies at the mode spacing of 765 kHz are too fast for the response times of solid-state or fiber gain media (~1 kHz) but are well within the semiconductor gain response time (~10 GHz). As such, it has been reported that use of a semiconductor gain medium in modelocked lasers suppresses the supermode levels by >10 dB [15–17]. Because the gain always saturates to a level near the net intracavity loss, the further the SCOW-COEO optical cavity is operated above threshold, the deeper the SCOWA operates into saturation (resulting in a larger intracavity power). The higher saturation level of the VC-SCOWPD system leads to an enhanced suppression of sidemode oscillation. Note that this suppression mechanism applies to all intensity noise processes below the inverse carrier lifetime.

It is useful to evaluate the performance of a DSC50S + RF amplifier COEO operating at similar levels of intracavity optical power. Figure 3 shows the measured phase-noise performance of a DSC50S + RF amplifier system using a 90:10 output coupler in the optoelectronic loop. The 90:10 coupler changes the distribution of power between the optical and optoelectronic cavities.

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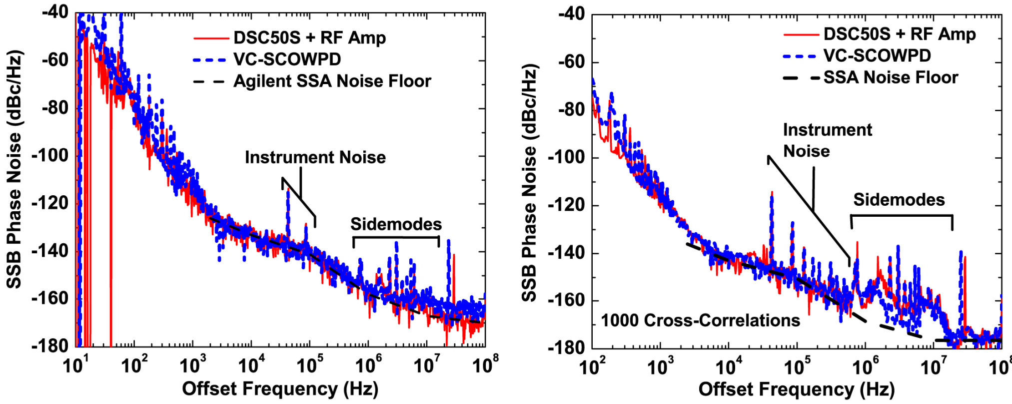

(a) (b)

Fig. 3. Measured phase-noise of a DSC50S + RF amplifier SCOW-COEO system (red line) using a 90:10 coupler (a) without cross-correlation averaging and (b) with 1000 cross-correlation averaging. The measured phase-noise of the VC-SCOWPD system is also shown for comparison (blue dashed-line).

Also shown in Fig. 3 is the comparison phase-noise of the previous VC-SCOWPD RF-amplifier-free SCOW-COEO system. Figures 3(a) and 3(b) differ primarily in measurement noise-floor and offset frequency range. In Fig. 3(b), one-thousand (1000) cross-correlation averaging was used in order to reduce the system noise-floor. The offset frequency range was correspondingly reduced to prevent long averaging times (>10 minutes). The DSC50S system was operated at 21.9 mA average photocurrent yielding an intracavity optical power of ~270 mW. The measured phase-noise of the two systems compares well with each other (<-115 dBc/Hz at 1 kHz offset) and to other high-performance COEOs found in literature [4, 5, 7]. Furthermore, the sidemode levels are similar (<-135 dBc/Hz) as the intracavity power and saturation of the gain medium are comparable between the two systems. Note that photodiode amplitude-to-phase (AM-PM) noise conversion was not a limitation in any of our measurements. Typically, a photodiode must be operated at the photocurrent of zero conversion slope to prevent degradation from AM-PM noise processes [18]. However, we have experimentally measured the AM-PM conversion nulls for both the VC-SCOWPD and DSC50S and found no significant change in phase-noise when operating around the vicinity of the null.

In Fig. 2, we observed that the COEO with larger intracavity optical power performed with lower phase-noise. The intracavity power is inherently related to the Q of the optical cavity. In steady-state, the gain provided by the optical amplifier must saturate close to but less than the level of total loss [13]. The closer an oscillator operates to the condition of gain = loss, the larger its circulating power. As the net loss per roundtrip is clearly related to the cavity Q, the larger intracavity power can be thought of as a consequence of a higher Q oscillator. Following this reasoning, we next perform a set of experiments in order to specifically assess the dependence of COEO phase-noise on optical power. Figure 4 shows the phase-noise of the COEO as the intracavity optical attenuation is varied using a power-monitoring variable optical attenuator (VOA). The absolute level of loss added to the cavity is not known for certain as we can only monitor the intracavity power during the measurement. Our later calibrations, however, indicated that generally every 0.5 dB change in attenuation yields ~1 dBm change in optical power. Loss affects the signal during every roundtrip and thus greatly influences the cavity's optical power. In our experiments, attenuation levels corresponding to intracavity powers between 7 dBm and 20 dBm were tested as shown in Fig. 4. The tests were split over two trials (7–11 dBm) and (16–20 dBm) as we found mode hopping if the cavity was detuned too far from its initial operating point. For this measurement, we used the configuration of the SCOW-COEO comprising a DSC50S photodiode + RF amplifier with a 90:10 output coupler in the optical loop.

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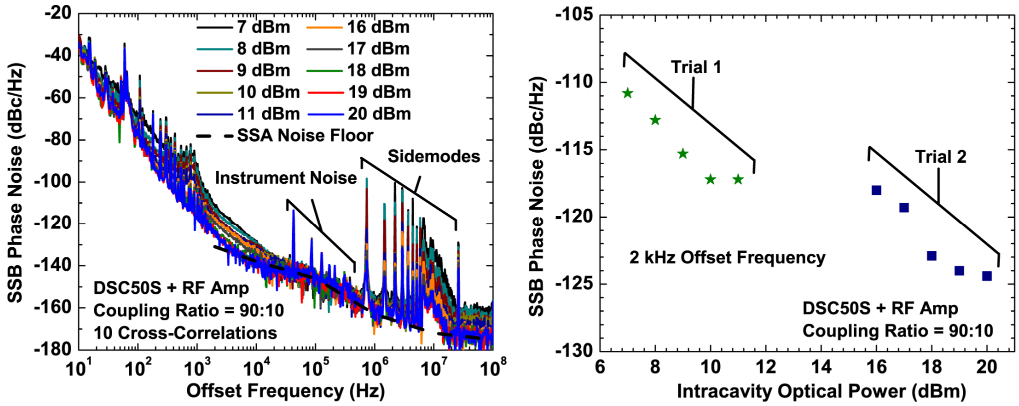

(a) (b)

Fig. 4. Measured phase-noise of a 90:10 output coupler DSC50S + RF amplifier SCOW-COEO system with varying intracavity optical power. The intracavity power was varied across two measurement trials (Trial 1: 7-11 dBm and Trial 2: 16-20 dBm), and the corresponding (a) phase-noise spectra and (b) phase-noise at 2 kHz offset frequency are provided.

As expected from our previous discussion, we find the cavity Q to significantly affect the phase-noise performance of the SCOW-COEO. Figure 4(a) shows the measured phase-noise spectra of the oscillator. With decreasing Q (increasing attenuation and decreasing intracavity power), both the phase-noise and the sidemode levels increase. The variation in phase-noise is as high as 14 dB near 2 kHz offset, while the maximum variation in sidemode spurs is ~40 dB. Note that the apparent increase in phase-noise beyond 20 MHz (past the RF filter bandwidth) is an artifact of the SSA's degradation in minimum sensitivity when the input RF power becomes too low. At low frequencies ($f < 100$ Hz), we believe the COEO to be affected by noise that is common to all attenuation levels, such as noise due to modelocking instabilities or to the environment. Figure 4(b) shows the measured phase-noise at 2 kHz offset frequency as a function of the intracavity optical power. As expected, the measurements indicate a trend of decreasing phase-noise with increasing optical power. Finally, although not shown here, we have also performed experiments varying the bias current of the optical amplifier and also varying the coupling ratio in the optical loop that yielded similar results to that of Fig. 4. Therefore, we have shown that the Q of the optical cavity significantly impacts COEO phase-noise. However, we have not yet explained the relationship between the two. The case of the COEO is particularly difficult to analyze as any modification to the electrical or optical loops affects both cavities.

To address these issues, we perform two separate experiments on the SCOW-COEO that evaluates the impact of Q when the operations of the individual cavities are isolated. Of particular interest in this investigation is the role of the 'Q-enhancement effect' on the phase-noise of a COEO [4, 6, 19]. The Q-enhancement refers to the filtering of the RF signal by the optical cavity and can be most easily understood by breaking the electrical loop between the output coupler and modulator input in Fig. 1. A test RF input is applied into the modulator terminal and the electrical response at the output of the RF coupler is observed. The optical cavity only allows modelocking at frequency multiples of the mode spacing and rejects modulation at frequencies outside the modelocking bandwidth. Thus, we expect that certain frequency ranges of the input signal will become filtered by the optical cavity response. The Q-enhancement effect has been characterized previously using S21 measurements to probe the electrical input-output relation of a COEO [4]. We have also performed S21 measurements on the SCOW-COEO (using DSC50S + RF amplifier) and found agreement only when both the electrical probe signal is small and the optical cavity is operated slightly above threshold. Ideally, a pump-probe experiment should be conducted with a large signal setting the modulation of the modelocked laser and a small signal probing the response of the cavity to noise perturbations.

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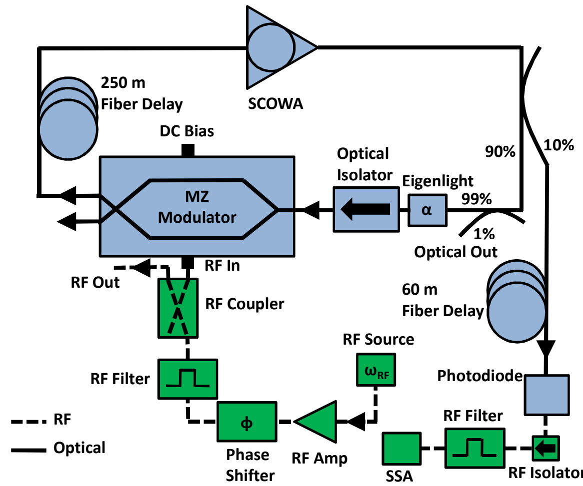

Fig. 5. Schematic of system for measuring the SCOW-COEO optical cavity response.

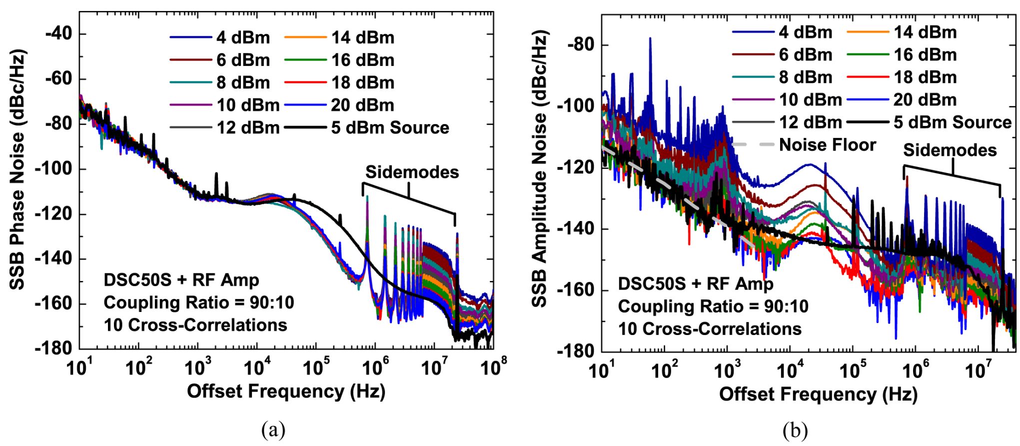

Fig. 6. Measured (a) phase-noise and (b) amplitude-noise of a 90:10 output coupler DSC50S + RF amplifier modelocked laser system with varying intracavity optical power. The noise of the reference RF source (black line) and noise-floor for the amplitude measurements (gray dashed line) are also provided.

In practice, we found this measurement difficult to perform because the leftover pump signal power becomes comparable to that of the probe even after filtering.

In our next two tests, we adopt a similar strategy to that of the S21 measurements and break our electrical cavity between the photodiode output and the RF phase shifter (Fig. 5). We apply a 5 dBm RF tone to the RF amplifier input so that the optical cavity is modelocked at a level similar to the operating point of the COEO. We then evaluate the output of the photodiode in terms of phase-noise and amplitude-noise performance and compare these measurements to the noise of the RF source. Through this comparison, we can directly assess the filtering of the source's noise by the response of the optical cavity. Furthermore, by varying the attenuation of the optical cavity, we can also investigate the effects of optical cavity Q on the SCOW-COEO's open-loop response. The phase-noise and amplitude-noise measurements at the output of the photodiode are shown in Figs. 6(a) and 6(b) along with the corresponding noise of the reference source. Note that the output of the photodiode passes through a 20 MHz bandwidth RF filter (Fig. 5) to prevent power at higher order beat products

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from reaching the SSA. For our comparisons, we have also applied the same filter to the output of the RF source.

In Fig. 6(a), we vary the intracavity optical power (4 dBm to 20 dBm) by adjusting the attenuation of a VOA and measure the resulting phase-noise at the output of the photodiode. Similar to before, every 0.5 dB change in attenuation generally yields ~1 dB change in circulating power. The sidemodes clearly increase as attenuation is increased; however, the phase-noise at all other frequencies appears to be unaffected. The increase in sidemode levels at lower power is again due to a decrease in amplifier saturation. The RIN of the amplifier adds to both the phase-noise and amplitude-noise of the photodetected RF output. It is clear from Fig. 6(a) that the residual phase-noise added by the SCOWA is far below the phase-noise of the RF source. It is worth noting that none of the measurements taken were limited by the noise-floor of the SSA. Furthermore, from the measurements in Fig. 6(a), we observe that the phase-noise of the optical pulse train follows that of the RF source until ~20 kHz offset. Beyond this frequency range, the source phase-noise becomes filtered by the optical cavity response. We find that the Q-enhancement effect appears to contribute negligibly to the COEO's low-frequency phase-noise performance. In fact, the filtering of RF source noise is well-known in modelocked laser literature [20, 21], and the filter frequency depends primarily on the length of the optical cavity. The negligible effects of Q-enhancement on the COEO's low-frequency phase-noise agree with recent phase-noise measurements of a high-performance slab-coupled optical waveguide optoelectronic oscillator (SCOW-OEO) [22]. The SCOW-OEO demonstrates ~-65 dBc/Hz phase-noise at 10 Hz offset for a 1.5 km length cavity, while the SCOW-COEO demonstrates ~-50 dBc/Hz at 10 Hz with a delay-length of 310 m (Fig. 3(a)). The phase-noise scaling is nearly $1/(\text{delay time})^2$ as according to theory.

Figure 6(b) shows the amplitude-noise spectrum tested with the same configuration and intracavity optical power range (4 dBm to 20 dBm) used in Fig. 6(a). Despite the limitation of the SSA noise-floor, it can be seen that the amplitude-noise generally decreases as the optical power increases toward + 20 dBm. At lower intracavity powers, the amplitude-noise rises above that of the RF source due to the RIN of the SCOWA. In this case, the added noise of the SCOWA can clearly be seen over the amplitude-noise of the RF source. This is in part due to the significantly lower amplitude-noise component of the RF source and also due to the higher sensitivity of the SSA's amplitude-noise measurement. The RIN of the optical amplifier decreases as the saturation of the amplifier increases. This reduction in RIN directly reduces the amplitude-noise added to the RF source, as can be seen in Fig. 6(b) for higher intracavity optical powers. Near 1 kHz offset, the measurable amplitude-noise (at higher optical powers) appears to decrease below that of the RF source. This is due to the suppression of the source's intensity-noise by optical amplifier saturation. The sidemodes decrease at higher intracavity powers in agreement with the measured phase-noise spectrum of Fig. 6(a). Although not explicitly shown here, we observed that both the measurements of Fig. 6(a) and Fig. 6(b) are insensitive to the RF source over a wide range of input power levels.

Based on these results, we conclude that the degradation of SCOW-COEO phase-noise in Fig. 4 is due to the increase of SCOWA RIN when the Q of the optical cavity is decreased. The oscillation of a COEO initiates from an intensity fluctuation, which must have random phase. Once oscillation is reached, further injection of incoherent RIN on top of a coherent RF signal results in broadening (amplitude and phase) of the RF spectrum. Therefore, the optical amplifier RIN of a single roundtrip is critical to the phase-noise performance of a COEO. The increase in RIN with decreasing optical cavity Q cannot be observed in the phase-noise of Fig. 6(a) over the noise of the RF source. However, Fig. 6(b) clearly shows the degradation of RIN with cavity attenuation. Before concluding this section, we wish to mention that the noise resonance located near 20 kHz offset in Fig. 6(b) is due to amplitude-noise resulting from timing differences between the RF source and the filtered optical pulse train [21]. Frequently, this noise also appears in the measurements of SCOW-COEO phase-noise. In such cases, we usually tune the RF phase shifter to optimize the COEO around a different operating

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frequency. Note that this noise feature also appears in the measured COEO phase-noise (Fig. 4) of Ref [5] and in the measured phase-noise of Ref [7].

3.2. SCOW-COEO RF spectrum and optical pulse train

In order to provide a complete characterization of the SCOW-COEO system, we next describe our measurements of the oscillator's RF spectrum and output optical pulse train. The configuration used for both of these measurements is the same as that of Fig. 1 with an 80:20 coupler and V_π ~3.0 V (at 10 GHz) modulator. The RF spectrum is shown in Fig. 7(a) for both the cases of the RF-amplifier-free VC-SCOWPD system and the DSC50S + RF amplifier system. The operation conditions are the same as that of Fig. 2. The measured signal powers out of a 10 dB RF coupler are 0.5 dBm and −3.0 dBm (after calibration of losses) with and without RF amplification, respectively. The loss of signal power is due to the lower overall gain of the RF-amplifier-free configuration. Beyond ~1 MHz, the spectrum reaches the noise floor of the measurement system. With the VC-SCOWPD system, the sidemode spurs are below the noise-floor (−73.5 dBm) indicating a measurement-limited sidemode suppression of > 70.5 dB. However, with the DSC50S + RF amplifier configuration, a small sidemode peak (not noise) is visible at ~-3 MHz offset corresponding to a sidemode suppression of ~72.5 dB.

In addition to the previously described tests on the RF signal, we have also measured the optical pulse train properties of the SCOW-COEO's optical output. Figure 7(b) shows the compressed time-domain SCOW-COEO pulse shapes measured using an Agilent Infiniium DCA-J86100C oscilloscope with a 65 GHz Agilent 86116B optical sampling module. The optical output power of ~2 mW was compressed using 60 m of dispersion-compensating fiber (DCF). The compressed pulsewidths using the VC-SCOWPD and DSC50S + RF amplifier systems were both measured to be ~26.8 ps, while the corresponding uncompressed pulsewidths were ~32.2 ps and ~26.2 ps respectively. The DCF fiber compresses the pulses of the VCSCOWPD system but was not optimal as the time-bandwidth product (TBP) was still ~1.8X transform-limited (~0.25 nm spectral bandwidth) assuming a Gaussian pulse-shape. Longer lengths of DCF fiber were not tested because they were not available at the time of the measurement. For the DSC50S + RF amplifier system, the 60 m DCF fiber introduces additional chirp to the pulses. The corresponding TBPs are ~1.3X (~0.17 nm spectral width) and ~1.1X transform-limited when the pulses are compressed and uncompressed, respectively. In this case, linear chirp does not significantly degrade the width of the measured optical pulses. The pulse widths measured compare well to that of other semiconductor-based COEOs but are significantly broader than those achieved by COEOs using either solid-state or fiber-based gain media. The pulse broadening experienced by semiconductor COEOs is usually attributed to nonlinearities of the semiconductor gain medium [23, 24].

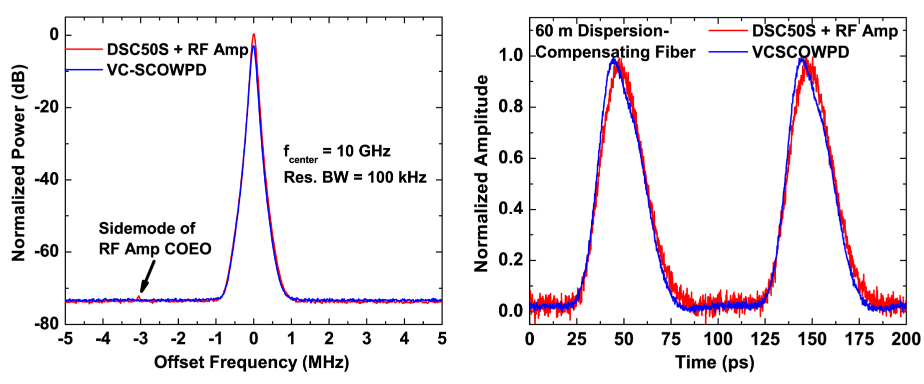

Fig. 7. Measured (a) RF spectrum and (b) optical pulse train of a VC-SCOWPD (blue line) and a DSC50S + RF amplifier (red line) SCOW-COEO system.

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4. Summary

We have shown the operation of a high-performance RF-amplifier-free SCOW-COEO operating at 10 GHz with low phase-noise (<-115 dBc at 1 kHz offset) and large sidemode suppression. The output optical pulses after compression were ~26.8 ps in width corresponding to 1.8X the transform-limit for a Gaussian pulse-shape. Furthermore, we found that the COEO phase-noise performance degrades significantly with attenuation in the optical cavity. Separate measurements probing the optical cavity response show this performance loss to be due to increase in the optical amplifier RIN. The Q-enhancement effect does not appear to significantly improve the low-frequency phase-noise of a COEO.

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