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Single-longitudinal-mode, narrow-linewidth oscillation from a high-\( Q \) photonic-electronic hybrid cavity

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Received August 24, 2016; accepted October 14, 2016; posted online December 8, 2016

We propose a high-\( Q \) photonic-electronic hybrid cavity for single-longitudinal-mode narrow-linewidth oscillation, where part of the cavity is in the radio frequency (RF) domain by a pair of frequency conversions. In the RF part, we can easily achieve MHz filtering and a large delay by inserting an electronic filter. In mathematics, we prove that the frequency conversion pair and electronic filter in between can be equivalent to a high-\( Q \) optical filter cascaded low-noise optical amplifier as a whole. Finally, the 20-dB bandwidth of oscillation is 1/20 of that of an optical local oscillator, and the maximum phase noise suppression can reach 65 dB.

OCIS codes: 140.3410, 230.0250, 140.3570.

doi: 10.3788/COL201715.010010.

The single-longitudinal-mode (SLM) narrow-linewidth laser is very important in coherent systems, such as advanced optical fiber communications and optical sensing. Specifically, an SLM laser with a narrow linewidth allows for both higher-order modulation and highly sensitive signal detection, which are the key elements to improve transmission capacity in next-generation optical networks. A similar laser is also desired in optical remote sensing applications, such as imaging laser radar, where the low phase noise extends the detection range greatly. It is well known that the ultimate laser linewidth is inversely proportional to the square of the laser cavity quality factor (\( Q \)-factor), given by the Schawlow–Townes limit. The \( Q \)-factor can be expressed as \( Q = 2\pi f\tau_s \), where \( f \) is the optical carrier frequency and \( \tau_s \) is the photon lifetime. As \( \tau_s \) is increased, more photons are stored in the cavity, so the relative contribution of phase diffusion due to spontaneous emissions into the lasing mode is reduced, as is the laser linewidth. Therefore, a narrow linewidth can be obtained easily by extending the laser cavity delay while maintaining the cavity loss. Thus, the characteristics of ultralow loss (less than 0.2 dB/km), as well as compact size and no alignment requirement, make optical fibers a good choice for narrow-linewidth laser cavities.

However, a long fiber cavity will lead to multi-modes or mode hops due to the greatly decreased longitude mode interval, i.e., the free spectral range (FSR, given by \( 1/\tau_s \)). The general method to realize SLM selection is inserting the appropriate optical filter(s) into the cavity, such as two or multiple fiber rings, Fabry–Perot (FP) resonators, or incorporating fiber Bragg gratings and saturable absorbers. But the disadvantage of most existing optical filters is that most of filters with a single stage (such as a single ring) can hardly provide a narrow filtering bandwidth and large filtering FSR simultaneously. If we combine several filters to improve its whole performance, its physical features (such as the central wavelength, bandwidth, or delay) are more likely to be affected by temperature drifting and mechanical vibrations (especially when the filtering bandwidth is very narrow). In addition, some fiber nonlinearities can also be used to realize SLM selection by their equivalent narrowband optical filtering effects. For example, the stimulated Brillouin scattering (SBS) effect can provide only MHz filtering bandwidths, which is similar to the self-adapted grating generated by saturated absorption in unpumped erbium-doped fibers (EDFs). Moreover, similar optical filtering can be realized even by random Rayleigh backscattering. In these conditions, a high optical power is indispensable, which increases the complexity of system. So a simple and feasible way is to insert a fixed narrowband optical filter into a short cavity directly (e.g., an integrated structure). Due to the Kramers–Kronig relation, such narrowband filtering is always accompanied by a large delay (the so-called slow light filter), resulting in simultaneous SLM selection and large cavity delay. The amplitude and phase noises of lasers are also demonstrated to be dramatically quenched by a few orders of magnitude by such optical filtering. Because of the very high carrier frequency (∼193 THz at the usual communication band), MHz optical filtering usually requires the \( Q \)-factor (defined as the carrier-dividing bandwidth) to be around 10\(^8\). Although even higher \( Q \)-factors have been demonstrated by free-space etalons or integrated devices, the 10\(^8\) level is hard to realize for most labs.

The current filter \( Q \)-factor challenge comes from the huge difference between the optical carrier frequency and the filtering bandwidth. Rather than fabricating such
a high-$Q$ device directly, we here propose that the required $Q$-factor can be greatly reduced ($\sim 10^6$ reduction) by slowing down the optical carrier. The optical carrier is first down-converted to an electronic carrier ($\sim 100$ MHz in our experiment) by an optical local oscillator (LO), and the electronic carrier is then bandpass filtered by an electronic filter, which is finally up-converted to the optical domain with the same optical LO. With the help of frequency conversion pair, the challenging narrowband optical filtering is achieved equivalently within the electronic domain, which is much easier for MHz-level or less filtering due to the greatly decreased carrier frequency. Since the Kramers–Kronig relation is independent of the carrier frequency, a large delay is also obtained in electronic domain. Further, if we connect the input and output of this frequency conversion pair directly, a resonance cavity appears. Note that the resonance frequency changes greatly in this cavity: it is $\sim 100$ MHz between the down- and up-conversions, while it is around $193$ THz elsewhere. So we believe we propose, for the first time, the concept of a “photonic and electronic hybrid cavity.” Since we use electronic filtering instead of optical filtering or fiber nonlinearity, the whole system becomes simpler and insensitive to environmental disturbances. One obvious advantage of our scheme is that the filtering bandwidth can be easily adjusted by the electronic filter, and this filtering is absolute SLM filtering. It is worth mentioning that our scheme looks a little like the traditional optoelectronic oscillator (OEO) because of their common O-E-O resonator. In fact, these two structures are totally different. The reason is that the purpose of traditional OEO is to obtain high-quality microwave signal. In general, it is an intensity modulation and direct detection (IM/DD) system, and most of cavity delay is provided by the fiber. But our scheme is used to achieve a high-quality lightwave signal. We use frequency modulation and coherent detection, and most of the cavity delay is provided by the electronic part. So from our point of view, our scheme enriches and expands the traditional OEO model.

Previously, in Ref. [23], we proposed this frequency conversion pair and proved that the significant phase noise of the optical LO that drives the frequency conversion pair can be counteracted itself by delay matching. In this Letter, we will continue to prove that the frequency conversion pair and electronic filter in between can be equivalent to a high-$Q$ optical filter cascaded low-noise optical amplifier. This equivalent can help us to understand the oscillation mechanism of this novel cavity. Since the above optical-to-electronic down-conversion, the electronic-to-optical up-conversion, and the electronic bandpass filter are all very mature, we built the photonic-electronic hybrid cavity with off-the-shelf devices. The final results show it is similar to traditional all-optical cavities, and its SLM oscillation shows a much narrower linewidth than the optical LO we used: the 20-dB linewidth is 20 kHz, 1/20 of the optical LO. The phase noise suppression ratio can reach 65 dB near the frequency offset of 200 kHz.

Figure 1 shows the setup of the frequency conversion pair and the electronic filter in between, the core part of our photonic-electronic hybrid cavity. It consists of a coherent receiver (i.e., a $2 \times 2$ optical coupler, OC and a balanced photoelectric detector, BPD), a low-noise amplifier (LNA), an acoustic-optical modulator (AOM), a piece of delay matching fiber, and an SLM LO at 1550 nm. We use the coherent receiver as the optics-to-electronics down-converter. The AOM has an electronic characteristic that if the frequency of the electronic-driven signal deviates from its central frequency (100 MHz), the optical insertion loss will increase, like a filter. So we use the AOM as an electronic filter (3-dB bandwidth of 14 MHz) cascaded E-O up-convertor. Since the input (point A) and output (point B) are all lightwaves, we can generalize all devices in between as a black box and define its optical transfer function. In Ref. [23], we proved that the phase noise of the LO will not mix into the output if the optical delay introduced by the delay matching fiber matches the electronic delay introduced by the electronic filter. So in the following derivation, we can ignore the phase noise of the LO. Beyond that, the amplitude noise of the LO can also be ignored because the relative intensive noise (RIN) of the laser is very small most of the time. Moreover, we do not need to take into account the gain between A and B for the moment (this will be analyzed in the next paragraph). Assuming the optical field of the LO is $\exp(i\Omega_0 t)$ and its Fourier transform is $2\pi\delta(\omega - \Omega_0)$, the optical spectrum of the input $S_{\text{in}}(\omega) = S(\omega - \Omega_0 - \omega_0)$, where $\Omega_0$ is the angle frequency of the input optical carrier and $\omega_0$ is the electronic central angle frequency of AOM. After down-converting, electronic filtering, and up-converting, we can determine the output optical spectrum $S_{\text{out}}(\omega)$. The optical transfer function $T(\omega)$ of this black box can be defined as the output spectrum dividing the input:

$$S_{\text{out}}(\omega) = [S(\omega - \omega_0) \cdot H(\omega - \omega_0)e^{i\omega t_0}]$$

$$\otimes \delta(\omega - \Omega_0)e^{i\Omega_0 t_0},$$

(1)
$T(\omega) = S_{out}(\omega)/S_{in}(\omega) = H(\omega - \Omega_0 - \omega_0)e^{i\omega_0}$.  

In Eq. (1), $H(\omega - \omega_0) \cdot \exp(j\omega t_0)$ is the full response of the electronic filter, whose central angle frequency and delay are $\omega_0$ and $t_0$, respectively. We can see that at this O-E-O process, the central angle frequency of the filter changes from $\omega_0$ to $\Omega_0 + \omega_0$ in Eq. (2). That is to say, the electronic filtering in between has been moved intact to the optical domain, including the amplitude frequency and phase-frequency response. So we can regard this black box as an optical filter whose bandwidth and delay depend totally on the electronic filter. Because the carrier frequency almost increases by $2 \times 10^6$ times (from 100 MHz to 193 THz) while the 3-dB bandwidth remains, the equivalent $Q$-factor of this optical filter increases accordingly and reaches $1.4 \times 10^7$.

Due to the down-conversion, electronic amplification, and up-conversion, the equivalent optical filter has obvious gain and additional noise. In the following, we will derive the small-signal gain and noise figure (NF) of this black box. Assume the powers of the input optical carrier and LO are $P_s$ and $P_{LO}$, respectively. After down-conversion, the power of the radio frequency (RF) carrier is $2R_s^2P_sP_{LO}R_s$, where $R_s$ and $R_i$ are the responsivity and internal impedance of the BPD, respectively. When up-converting, the AOM has an intrinsic optical insertion loss ($\sim$5 dB), and its optical transmittance is proportional to the power of the RF carrier that drives it. So after electronic amplification and up-converting, the output optical power is proportional to $R_s^2P_sP_{LO}^2gR_s$, where $g$ is the total electronic gain. So we can express the total optical gain of this black box as

$$G \propto R_s^2P_s^2P_{LO}^2gR_s. \quad (3)$$

When the power of the optical LO is high enough, the thermal noise of the BPD is relatively small, while the RIN is well suppressed due to the balanced detection (the typical suppression ratio is larger than 20 dB). As a result, the shot noise dominates the output noise of the BPD. Note that the following LNA is limited by thermal noise. The typical NF of a narrowband RF amplifier around 100 MHz can approach even 1, i.e., the sensitivity is much lower than the output shot noise power of the BPD. As a result, we believe the total additional noise is determined by the shot noise of BPD. The power spectrum density (PSD) of the shot noise can be calculated as $2qR_s^2P_{LO}R_s$, where $q$ is the electron charge. Similar to the above, the PSD of the optical noise after up-converting is proportional to $qR_s^2P_{LO}^2gR_s$. Just like ordinary optical amplifiers (e.g., erbium-doped fiber amplifiers, EDFA), this noise can be analogous to the amplified spontaneous emission (ASE). Compared with Eq. (3), we can find that the PSD of this equivalent ASE can be simplified as $S_{ASE} = qG/R_s = h\omega_sG/n$, where $h\omega_s$ is the single-photon energy and $n$ is the quantum efficiency. It is well known that for ordinary optical amplifiers, the PSD of the ASE can be expressed as $S'_{ASE} = n_sp\omega_s(G - 1)$, and NF is $F = 2n_sp(1 - 1/G) + 1/G$, where $n_sp$ is the spontaneous emission factor. By comparing $S_{ASE}$ and $S'_{ASE}$, we can find that it is feasible to replace $n_sp$ with $1/n$ and obtain the equivalent NF of our black box accordingly when $G \gg 1$:

$$F \approx \frac{2}{n} + \frac{1}{G} \approx 3 \text{ (dB)}. \quad (4)$$

The 3 dB result is obtained under the condition of $n \approx 1$, and this is satisfied in our low-speed BPD. This means that the noise characteristic of our black box is superior to most ordinary optical amplifiers (e.g., the NFs of commercial EDFA are approximately 5 dB).

In order to prove these theoretical predictions, we built a special system to measure the gain and NF of our black box. The setup is shown in Fig. 2(a). The powers of the optical LO split by OC1 for down- and up-converting are 1 and 10.5 dBm, respectively. The input is frequency shifted by 100 MHz (by AOM2, which is same as AOM1), and its power can be adjusted by variable optical attenuator (VOA). The BPDs we use (BPD1 and BPD2) have an intrinsic gain of 23 dB and a bandwidth of 0.8 GHz. The gain of the LNA is 23 dB, and the insertion loss of AOM1 is 5 dB. The optical delay before up-conversion is matched to the electronic delay. The output power is measured by an optical power meter (OPM) to calculate the gain. The NF is defined as input signal-to-noise ratio (SNR) dividing the output SNR. The optical SNRs are all converted to the electronic domain by the BPD and measured by an electrical spectrum analyzer (ESA). The measured gain and NF are shown in Fig. 2(b). We can see that when the input optical power is small ($< -40$ dBm), the average gain and NF are 31.5 and 3.4 dB, respectively. Such noise performance benefits from the well-developed technologies of balanced detection and electronic amplification, which.

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Fig. 2. (a) Setup for parameter measurements of black box. (b) The measurement results of the gain and NF.
is superior to direct optical amplification. When the input increases, the amplifiers in the black box will be saturated, which generates the declining gain and ascending NF. This proof-of-concept test demonstrates that it is feasible to equate our proposed black box to a high-$Q$ optical filter cascaded low-noise optical amplifier.

The experimental setup for oscillation is shown in Fig. 3. The parameters of the components that belong in the black box are the same as those in the proof-of-concept test. In this experiment, we form the photonic-electronic hybrid cavity by connecting OC2 and OC3 (all 5:5) directly. Moreover, we add a polarization controller (PC) to adjust the polarization in the cavity. Because of the obvious optical gain brought by the black box, the cavity will oscillate in an appropriate polarization, like traditional cavities. Note that most of the cavity delay comes from the black box (∼180 ns), and the residual (∼20 ns) is provided by the OC and pigtails. These two parts constitute the whole cavity delay. A problem in the experiment is that the indispensable delay matching fiber is sensitive to technical noise, which may introduce an extra phase shift into the cavity. This will cause the 100-MHz RF carrier to drift within a 14-MHz passband, and then the output optical power fluctuates. In order to suppress frequency drifting and improve the power stability, we add a piezoelectric transducer (PZT) to compensate for the extra phase shift. The compensation signal comes from the optical power of the output. After power detection and the PID controller, we can get the control signal. This signal is then amplified by a high-voltage driver and feedback controls the PZT to maintain the maximum output optical power. The fibers we use are all standard single-mode fibers (SSMFs), and the refractive indexes of the fiber cores are all about 1.5, so the length of the delay matching fiber plus the PZT is calculated approximately as $1.8 \times 10^{-7} \times 3 \times 10^{8}/1.5 = 36$ m. We can change the AOM with a smaller electronic delay to reduce the length of the delay matching fiber plus the PZT. For example, if we maintain the 14-MHz filter bandwidth and the bandwidth-delay product can reach 1, the length can be reduced approximately to 15 m.

Similar to traditional all-optical cavities, our cavity has an oscillation threshold as well. We can regard the optical LO as the traditional pump and depict the relationship between the LO and output power as shown in Fig. 4(a). We can see the oscillation threshold is about 1 mW. When the power of the LO increases from 1 to 20 mW, the output power increases linearly. The slope efficiency is about 1.8%, and this is because of the big loss during the O-E and E-O conversions. Furthermore, the RIN is measured by imposing the cavity output to a low-speed PD-cascaded LNA (gain of 30 dB, amplifying frequency range is from 1 kHz to 1 GHz), and then having it Fourier analyzed by the ESA, which is shown in Fig. 4(b). The result shows that the RIN is lower than $-135$ dBc/Hz when the frequency is higher than 1 kHz. It will decrease below $-155$ dBc/Hz when the frequency is higher than 1 MHz. The inset shows the RIN in a span of 50 MHz. We can find the residual side mode near 5 MHz (corresponding to the ∼200 ns cavity delay). Its peak value is about $-155$ dBc/Hz, which is much lower than the close-in noise. This means our oscillator has a good SLM operation.

The oscillation linewidth is a big concern in our photonic-electronic hybrid cavity. Being different from the traditional ones, our cavity needs an optical LO, and its linewidth may affect the cavity output. In Ref. [23], we theoretically deduced that a precise delay match will entirely eliminate the significant phase noise of the LO at the output port of the black box. That is to say, a non-ideal delay match will degrade this elimination, and a part of the LO phase noise can mix into the output. This non-ideal effect will be accumulated in the cavity. So the linewidth of the final cavity output has a close relationship with the phase noise of the LO and the degree of delay matching. In order to show the relationship between the LO, delay match, and cavity output, we adapt two...
specific LOs. In the first case, we want to show the relationship between the output phase noise and delay match. In this case, the LO is a fiber laser (1550 nm, 3-dB linewidth is 1 kHz) that is single-frequency phase modulated by an RF signal. This is used to simulate phase noise at some specific frequency points (i.e., the side mode). The frequency range of the modulated signal is from 500 kHz to 1 MHz. We adjust the length of the delay matching fiber (i.e., adjusting the degree of matching). Then, we compare the two side-mode suppression ratios (SMSRs) of the LO and cavity output. The result is shown in Fig. 4(c). We can see a more precise delay match can increase the ratio between the two SMSRs (i.e., a better phase noise suppression), which will improve the linewidth of the cavity output directly. Moreover, the suppression ratio increases along with the decreasing frequency offset, which reflects that the more effective suppression appears in the low frequency range. These results all correspond with the theoretical predictions in Ref. [23]. In the second case, we want to show a comprehensive linewidth suppression between the LO and cavity output. In this case, the LO is the same fiber laser that is frequency modulated by a frequency-sweeping signal. The frequency modulation is realized by another AOM. We use the standard delayed self-heterodyne method to measure the linewidth of the LO and cavity output. The length of the delay fiber is 140 km. The result is shown in Fig. 4(d). We can see the LO has an approximately rectangular linewidth, and its 20-dB linewidth is about 400 kHz. After resonating in the cavity, the output is obviously narrowed and its 20-dB linewidth is about 20 kHz. The maximum suppression ratio appears near the frequency offset of 200 kHz, which is about 65 dB. We think the greater suppression is practicable when the frequency offset is below 200 kHz and the noise floor is limited. It is worth mentioning that the suppression will fail in the ultra-low frequency range (e.g., <1 kHz). We think in this range, some intrinsic noise, such as technical noise, will dominate our hybrid cavity and broaden the 3-dB linewidth of the output remarkably.

In conclusion, we propose a high-Q photonic-electronic hybrid cavity. In this novel cavity, MHz-level optical filtering and a necessarily large delay are easily realized by the fixed electronic filter in the RF part, which provides a new way to solve the problems of traditional all-optical cavities. We prove mathematically that the frequency conversion pair and electronic filter in between can be equivalent to a high-Q optical filter cascaded low-noise optical amplifier. In this equivalent, the Q-factor reaches as high as $1.4 \times 10^7$, and the NF approaches the 3-dB theoretical limitation. Finally, we set up this hybrid cavity with off-the-shelf devices and obtain SLM oscillators, like in traditional all-optical cavities. The results reveal the linewidth of the cavity output can be much narrower than the LO and the phase noise suppression ratio can reach 65 dB near the frequency offset of 200 kHz. The further advantages may be due to the variable-bandwidth electronic filter and tunable LO.

This work was supported by the National “973” Program of China (No. 2012CB315705), the National Natural Science Foundation of China (Nos. 61302016 and 61471065), and the NCET-13-0682.

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