Frequency synthesis of forced opto-electronic oscillators at the X-band

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Ultra-low phase noise performance is required for frequency agile local oscillators, which are the core for high resolution imagers, spectrum analyzers, and high speed data communications. A forced opto-electronic oscillator (OEO) benefits from frequency stabilization techniques for realizing a clean and low phase noise source at microwave and millimeter wave frequencies. Forced oscillation techniques of self-injection locking and self-phase lock loop are combined to provide an ultra-low oscillator phase noise both close-in and far-away from the carrier frequency, while a tunable yttrium iron garnet microwave filter combined with a wavelength tuned transversal filter are employed to implement both coarse and fine frequency tuning for a tunable X-band OEO. A phase noise of $-137$ dBc/Hz at an offset frequency of 10 kHz is achieved covering the frequencies of 9 to 11 GHz with a fine frequency tuning resolution of 44 Hz/pm and coarse tuning of 25 MHz/mA. Moreover, the long term stability of the output signal is tested, and a maximum frequency drift of 2 kHz is measured within 60 min for the X-band synthesizer.

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Microwave and millimeter wave local oscillators with a low close-in to carrier phase noise are required for high angular resolution phase shift keying modulation/demodulation at a high speed data transmission and high temporal accuracy radar imagers. Opto-electronic oscillators (OEOs) are used as a promising way for creating a high frequency radio frequency (RF) signal with a great spectral purity to meet many modern applications. The set-up of a classic OEO at the X-band is described in Fig. 1 within the dotted region, where to achieve the highest spectral purity, a very low noise long fiber delay length is required along with a narrow passband microwave filter. The low relative intensity noise (RIN) fiber laser (Optilab TWL-C-HP-M) along with a high power handling photodetector (Discovery Semiconductors-DSC50S) could provide a low noise figure fiber optic delay line. Moreover, a dual drive Mach–Zehnder modulator (DD-MZM) is used to reduce the noise figure of an optical link. The long length of the delay line improves the close-in to carrier phase noise at a square of the delay line length, but unfortunately it satisfies many other oscillation modes within the passband of a narrow-band electrical filter. A high quality ($Q$) factor mechanically tuned metallic cavity filter is employed for the generation of X-band oscillation signals over 8–12 GHz. The classic OEO performance is primarily limited based on the close loop behavior, and its frequency tuning is quite limited because of the fixed passband characteristic of a metallic cavity filter. Moreover, the presence of multi-mode oscillations is to be minimized using optical transversal concepts by rejecting the side-mode. In order to achieve the fast broadband tuning required in frequency synthesizers, an electronically tuned yttrium iron garnet (YIG) filter will be introduced in this Letter to replace the role of the mechanically tuned high $Q$ metallic filter. Meanwhile, in order to compensate for the low $Q$ factor of a widely tunable YIG filter, an optical transversal filter is used as a wavelength tunable narrowband microwave filter.

Fig. 1. Block diagram of a fixed frequency OEO using a narrowband metallic cavity filter and its forced oscillation using SIL and SPLL.
is used as main loop of the OEO, and the other path is further split into two equal optical power paths, which are then used as the dual phase locking signal. The combined phase locking signal is then input into a custom designed printed circuit board (PCB)-based circuit for phase detection, low pass filtering, and amplification (i.e., the “Mixer + LPFA” block in Fig. 1). A double balanced mixer is integrated on the same board with a low pass filter amplifier [LPFA, realized using operational amplifier (Op-Amp) circuits] to work as a phase detector and the low pass portion of the phase lock loop (PLL)\(^2\). The phase error of the OEO main loop is compared with the dual delay lines of the PLL, and the phase error signal is fed back as a low frequency phase control through the direct current (DC) bias port of the MZM using a bias-T circuit. The SIL signal takes advantage of the PLL path and shares the same fiber used in the SPLL path. The SIL signal is split from one PLL signal and directly injected into the output of the metallic cavity. The injected power level ratio is expressed as \(\rho = \frac{P_i}{P_o}\), where the injected signal power is \(P_i\), and the OEO power level is \(P_o\).

The novelty of this Letter is the development of an SILPLL OEO-based X-band frequency synthesizer as compared to the earlier reported fixed frequency reports. Fine tuning of the optical transversal filter is combined with coarse tuning of the YIG filter to achieve a highly stable OEO with full electronic synthesis over 9–11 GHz. Performance of this synthesizer is evaluated in terms of its measured close-in to carrier phase noise and its long term frequency stability over 60 min.

A block diagram of the classic OEO design and forced oscillation using SILPLL is displayed in Fig. 1. The classical OEO block diagram is provided inside the dotted square in Fig. 1. The close-in to carrier phase noise of the OEO is measured using a R&S FSWP-26 phase noise analyzer and is depicted in Fig. 2 for different fiber optic delay line lengths using a low RIN (i.e., \(-157\) dB/Hz) fiber laser as the optical source, a DD-MZM (JDSU), a constant output power EDFA (1550-CP-V), a high power handling photodiode, and electrical amplifiers with the high-Q metallic cavity filter. Various fiber optic delay loops (\(L = 100, 500, 1000\) m) are employed as the main delay. The OEO output power is 8 dBm with a mechanically tuned 10 GHz oscillation selected by the metallic cavity. At an offset frequency of 10 kHz, the 100 m main loop provides a \(-105\) dBc/Hz close-in to carrier phase noise, while the 500 and 1000 m OEO provides \(-118\) and \(-124\) dBc/Hz, respectively. A lower close-in to carrier phase noise performance is expected for the 1000 m length due to a higher oscillator Q factor\(^2\). The achieved results follow a 20 dB/decade slope for fiber delay lengths before the offset frequency of 70 kHz. However, as with any fiber length increase in the main loop, the OEO frequency will be more sensitive to temperature variations and results in a larger number of side-modes inside the passing band of the metallic filter, which dramatically increase the integrated timing jitters\(^2\). A large number of side-mode peaks would also exist for longer than the 1 km fiber delay lengths. Therefore, the forced oscillation techniques of SIL, SPLL, and SILPLL have been developed to further reduce close-in and far from the carrier frequency\(^1\).

The oscillation frequency of the OEO is being controlled by using the narrowband metallic filter. A 19 inch rack mount system has been developed with a fixed frequency of operation\(^2\); however, a fully functional rack-mountable frequency synthesizer is very much in demand. An electronically tuned narrow bandpass filter using a YIG filter is considered due to its broadband tuning. However, the precise adjustment of the biasing current using a computer controlled power supply (Agilent E3631 A) is required to stabilize the opto-electronic oscillation frequency, since the YIG filter is very sensitive to any fluctuations in the bias current. A commercially available YIG filter (e.g., Avantek YF85-0107) is employed in our realization of a frequency synthesizer. As shown in Fig. 3, a frequency tuning sensitivity of 25 MHz/mA is measured when the YIG filter is tuned from 8 to 16 GHz.

However, due to the relatively low Q factor of the YIG filter compared to the metallic cavity filter, a broader passband is observed, which significantly increases the number of the oscillation side-mode peaks of the OEO. Therefore, an additional filtering mechanism is required to reduce the filter bandwidth to narrow the passband of the YIG filter, and a narrowband optical transversal filter is considered.

An optical transversal filter, as reported in Ref. \(^7\), could provide a narrowband filtering of microwave signals.
A first-order transversal filter, as depicted in Fig. 4, consists of two 3 dB optical-fiber-based couplers with two separate paths, where one is considered as a delay compared to the reference path.

The filter transfer function in terms of RF filtering is

\[ T(\omega) = \frac{1}{2} \left| 1 + \cos(\tau_d + \tau_D) \right|, \]  \hspace{1cm} (1)

where \( \tau_d \) is the fiber delay at the fiber laser wavelength, and \( \tau_D \) is the term due to the fiber dispersive delay. A standard SMF-28 fiber is used as the fiber delay and reference with a 30 m difference. From Eq. (1), the passband of the transversal is related to the laser wavelength. With the option of 1527 to 1567 nm wavelength tuning in the fiber laser source (smallest step 1 pm), the passband tuning of the transversal filter is measured and depicted as close to 10 GHz in Fig. 5.

With the help of the transversal filter, a fine tuning of 44 Hz/pm could be achieved in the frequency synthesizer and reduce the number of oscillation side-modes.

When the broadly tuned YIG filter is cascaded with an optical transversal filter, then the combined filtering significantly helps to reduce the oscillation mode numbers passing through the YIG filter. The cascaded topology of these two filters provides a 3 MHz passband and a frequency selectivity (an associated \( Q \) factor of 3300) even better than the baseline performance of the metallic cavity filter (with \( Q = 2000 \)). The inherently ultra-narrow, periodic, and tunable passband characteristics of the combined filters is used to covert the fixed frequency OEO to a full computer controlled frequency synthesizer. Figure 6 is the coarse tuned OEO-based synthesizer output using a YIG filter cascaded with the transversal filter. The center frequency is, in this case, selected to be close to 10 GHz, and a 1 mA change in the biasing current brings an approximately 25 MHz shift in the synthesizer output frequency. The fine tuning for the synthesizer frequency is displayed by a computer controlled fiber laser wavelength adjustment in steps of 0.8 nm and wavelength dependent dispersion characteristics of fiber delay line, \( \tau_D \). The fine tuning of the optical transversal filter and the resultant OEO frequency synthesis is depicted in Fig. 7, when the fiber laser is tuned to wavelengths of 1567, 1554, 1540, and 1527 nm for about a 10 GHz oscillation frequency of the OEO.

A block diagram of the forced OEO realized using the cascaded YIG filter and the transversal filter is depicted in Fig. 8. A push–pull amplifier with a gain of approximately 10 dB is used to drive the DD-MZM; the output of DD-MZM will be amplified by the constant output power EDFA. The output power of the EDFA is divided into either two or three optical paths for either using a single or a dual SIL (DSIL) loop, respectively. The loop with length \( L \) is the main oscillation loop of the OEO and another two paths are used for a dual SILPLL (DSILPLL)\(^{12,13}\). The first loop is the main loop of the OEO, and it is designed to satisfy an oscillation at 10 GHz by narrowband filtering at 10 GHz using the tuned YIG filter and the narrowband transversal filter to 10 GHz with a frequency resolution as high as 44 Hz. The tunable transversal filter is realized with 30 m of fiber delay [e.g., Corning...
SMF-28 with a dispersion of 17 ps/(nm·km) at 1550 nm for the fiber laser output wavelength of 1548 nm. The output from the transversal filter will then be input to the YIG filter, AMP1, and the push–pull amplifier, and then applied to the DD-MZM meeting the Barkhausen oscillation condition. The second loop of 3 km is shared by the SIL and SPLL, while the 3 and 8 km delay loops are then input to the “Mixer+LPFA” for the dual SPLL (DSPLL). The third loop of 7 km is to function as the extra injection locking loop.

The performance of SIL is evaluated by disconnecting the phase locking part of the system. A 7 km optical fiber delay is applied as an SIL to the OEO-based system with a main oscillation loop of $L = 1$ km and, the close-in to carrier performance depicted in Fig. 9. A phase noise of $-124$ dBc/Hz is measured at an offset frequency of 10 kHz, while a phase noise of $-93$ dBc/Hz at a 1 kHz offset frequency is measured. The performance using SIL with an improved RF filter is close to the result collected from the high Q metallic filter. Meanwhile, the SIL experiment is also performed by tuning the cascaded filter to the synthesized oscillation frequencies of 9 and 11 GHz in addition to 10 GHz, which confirms similar performance over the frequency synthesizer operation range. However, two side-mode peaks appear at 28 and 110 kHz with power levels of $-80.0$ and $-85.5$ dBc, respectively.

DSIL is useful to further suppress side-mode peaks. In an SIL configuration, a longer delay line of 7 km is used in the system for a better phase noise reduction. However, this long length will bring a lot of side-mode peaks that primarily originate from the spurious oscillation caused by the 7 km fiber delays. These side-mode levels are decided by the frequency selectivity of the cascaded RF filter. So with the fixed RF filter, we could only introduce another different non-harmonic delay line in the SIL loop. A dual injection locking configuration using 3 km with 7 km provides $-95$ dBc/Hz phase noise at the offset of 1 kHz and $-126$ dBc/Hz at a 10 kHz offset. Also, the level of the side-mode peak at 28 kHz was reduced to the $-95$ dBc level with the help of the second injection locking loop.

Since a good suppression for side-mode peaks is observed using DSIL, as shown in Fig. 10, then the phase locking of 3 and 8 km fiber delays are incorporated for a further reduction of the phase noise performance in close-in to carrier frequency using the dual phase locking delay lines. Because of a similar theory, using a dual loop here is aimed at reducing the side-mode peaks that are introduced because of the OEO delay lines, while further reducing the close-in and far-away from carrier phase noise levels. The single SIL with DSPLL (SILDSPLL) system provides a phase noise of $-103$ dBc/Hz at an offset frequency of 1 kHz and $-135$ dBc/Hz at an offset of 10 kHz, as depicted in Fig. 11. The suppression for the side-mode peak is also clearly seen in Fig. 11, when compared with DSIL, as depicted in Fig. 10.

DSIL and phase locking is a more complex configuration, but it combines the advantage of injection locking and phase locking in both close-in and far-away from the carrier frequency. The results depicted in Fig. 12 demonstrate the
best side-mode peak suppression for DSIL dual phase locking loop (DSILDPLL). Only one peak of −127.5 dBc is observed in the phase noise measurement. The phase noise performance is close to the performance depicted in Fig. 11. The phase noise reaches −105 dBc/Hz at 1 kHz and −137 dBc/Hz at an offset of 10 kHz for all of the synthesizer frequencies over 9–11 GHz.

The long term frequency stability of the OEO-based synthesizer is also studied over the X-band. The frequency drift of the oscillator is tracked over a time of up to 60 min using the max-hold feature of a R&S FSWP-26 phase noise analyzer. The frequency stability measurements of the SIL synthesizer operating at 10 GHz are depicted in Fig. 13 for a single run versus the max-hold results over 30 and 60 min. The span for the measurement is 50 kHz, and the resolution bandwidth is 50 Hz, while the video bandwidth is 30 Hz. The synthesizer output frequency shifts of 3 kHz are measured in 30 min, while in 60 min the center frequency will shift by 3.5 kHz. The comparison of the frequency stability of the SILPLL synthesizer is also measured, where only a 2 kHz frequency drift is measured at a center frequency of 10 GHz for both 30 and 60 min, as depicted in Fig. 14.

The phase noise performance of a forced OEO-based frequency synthesizer is demonstrated here operating over the X-band. The broadband frequency synthesis with a frequency resolution of 44 Hz is achieved using the electronic tuning of a cascaded narrowband filter using the YIG filter with an optical transversal filter. Coarse tuning of the frequency synthesizer is achieved by an accurate bias current control of the YIG filter, while fine tuning is realized using wavelength control. Forced oscillation techniques are also used to reduce the side-mode peaks and achieve very low close-in to carrier phase noise. Using a combination of DSILPLL provides a significant reduction of phase noise in the offset frequency range, reaching −137 dBc/Hz at an offset frequency 10 kHz for a frequency synthesis of 9–11 GHz within the X-band. The long term frequency stability shows a maximum frequency drift of 2 kHz over 60 min. With the demonstration of reliable frequency synthesis over the X-band, the realization of a highly stable OEO in a 19 in. rack mount system is now readily available.

References