Optoelectronic Oscillators: Recent and Emerging Trends

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Abstract

Highly stable oscillator are key in many important applications, where coherent detection is performed for improved detection. OEO (Optoelectronic oscillator) exhibits low phase noise at microwave and millimeter wave frequencies, attractive for applications such as synthetic aperture radars, space communication, navigation, and metrology. With advent of high data rate wireless communications carrier operating at frequencies above 10 GHz for high speed data transmission. The standard conventional OEO suffers from large number of unwanted closely spaced oscillation modes, large size, and thermal drift. The state-of-the-art reported X-Band and K-band OEO synthesizers incorporate a novel forced technique of self-injection locking double self-phase-locking (SILDPIL), which reduces the phase noise at close-in and far away from carrier, while suppressing side mode observed in standard OEO. As an Example, frequency synthesizers working at X-band (8-12 GHz) and K-band (16-24 GHz) is demonstrated, typically exhibiting phase noise at 10 kHz offset from the carrier better than -138dBc/Hz and -128dBc/Hz respectively. A fully integrated version of forced tunable low phase noise OEO is pursued for targeting fifth generation (5G), considering reduced size, power consumption, less sensitive to environmental effects, and cost.

1. Introduction

The electronic oscillators generate low phase noise signal up to a few GHz, but suffers phase noise degradation at higher frequencies, which is principally due to low quality factor (Q) resonator. The conventional approach for high frequency signal generation is frequency multiplier technique, but this technique suffers from higher phase noise due to AM-PM noise conversion [1] and sub-harmonics generation [2].

There are different types of resonators used in electronic oscillator circuits such as printed coupled transmission line (TL) resonators using surface acoustic wave (SAW) resonators, dielectric resonators (DR), ceramic coaxial resonators, yttrium iron garnet (YIG) resonators, and sapphire-loaded cavity resonators (SLC). These resonators have their unique characteristics and limitations, operate typically from 500 MHz to 20 GHz; however their quality factor degrade as operating frequency increases and at best limited to f x Q < 10^{14}. SLC based oscillator offers low phase noise signal generation, but has limited tuning and requires precise low temperature cooling system, which makes them expansive. The recent emerging technologies focus on metamaterial resonator based oscillator for microwave and millimeter wave applications [3]. The research effort towards improving the phase noise performances and tuning range of metamaterial resonator based oscillator led to explore Mobius topology for high frequency signal generation and signal processing [4]. (b)

Figure 1 shows a typical layout of printed Mobius Metamaterial Strips (MMS) resonator and its equivalent lumped L-C circuit model. Figure 2 shows the phase noise measurement setup for MMS inspired X-Band 10.24 GHz Oscillator. The achieved phase noise is -139dBc/Hz at 10 kHz for a 10.24 GHz carrier illustrated in Figure 3, where a narrow tuning range about 5% could be achieved with varactor diodes [4].

The novel approach for generating low phase noise synthesized signal source demonstrated in Figures (1)-(3) trades phase noise with tuning, therefore not suited for wideband applications. The optoelectronic oscillator (OEO) have advantages of high quality factor due to long storage delay using low loss optical fiber, potential for high frequency operation due to inherently broadband of electro-optic and opto-electronic transducers, and great immunity to electromagnetic interferences.
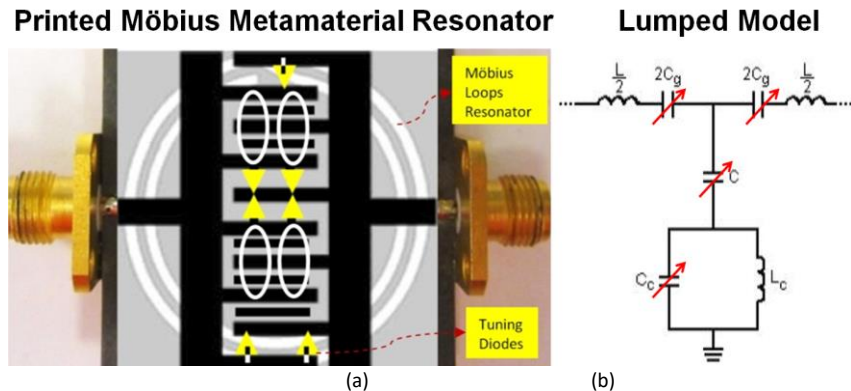

Figure 1: A typical Metamaterial based Möbius strips resonator: (a) layout. (b) Electrical equivalent lumped model circuits

Fig. 2: Phase noise measurement setup: X-Band 10.24 GHz synthesizers using MMS inspired Oscillator
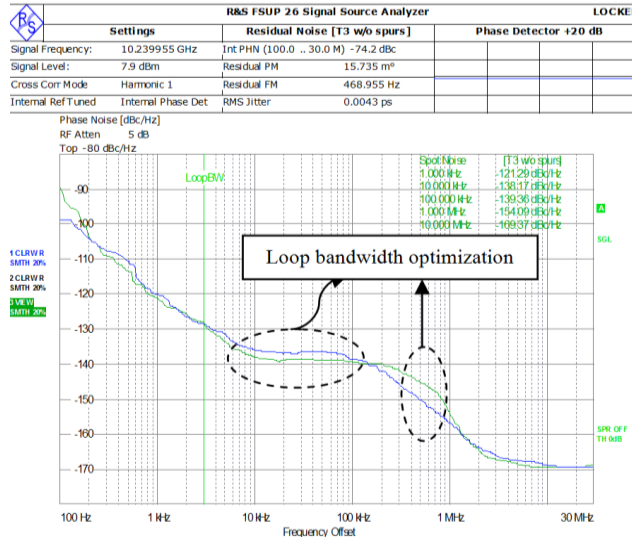

Fig.3: Measured phase noise plot of X-Band 10.24 GHz synthesizers using MMS inspired Oscillator

OEO

A typical OEO is a hybrid electronic and microwave photonic system, using an augmented positive feedback loop to facilitate low phase noise high frequency signal generation solutions. Yao and Maleki [5–7], first reported microwave signal generation using optical fiber delay line in 1996; the methods were based on converting the continuous light energy from a pump laser to radio frequency and microwave signals, may use optical fiber delay line or high quality (Q) factor optical resonators. The latter can be established on active or passive cavity. The low phase noise is ensured by the high quality (Q) factor of the feedback loop supported by the use of a long low loss optical fiber. The oscillation frequency is determined using a narrowband microwave filter. The OEO based on delay optical fiber loop suffers from multiple number of closely spaced oscillation modes, as these side-modes are multiple oscillation frequencies that could pass through narrowband microwave frequency filter. To guarantee single-mode oscillation, an ultra-narrowband high Q-factor microwave filter is needed, but such a filter is impossible to be realized. Optical filtering could be incorporated and the ones using optical resonators are difficult to implement and suffers from vibrational mode stability. Recently, Zhang and Yao [8] reported the single-mode operation without ultra-narrowband optical filter based on parity-time (PT) symmetry and two identical matching feedback loops, with one having a gain and the other having a loss of the same magnitude. As depicted in Figure (4), PT-Symmetric OEO utilizes polarization to implement tunable optical power splitting to the BPD, which is polarization sensitive and even minor vibrations can stimulus strong modulations on the phase and polarization state of the light wave propagating in the long optical loop. The measured phase noise plots reported by Zhang et al. as illustrated in Figure (5) compares the performance of PT-Symmetric OEO to state-of-the-art commercially available electronic generated microwave signal source [8]. As illustrated in Figure (5), PT-symmetric OEO is operating with 3- different loop lengths (20.31 m, 433.1 m, and 9.166 km); the phase noise at 10 kHz offset from the carrier frequency 9.76 GHz for the corresponding loop lengths measured typically −93dBc/Hz, −104dBc/Hz, and −143dBc/Hz. It is interesting to show that PT-symmetric OEO topology improves the phase noise performance at 10 kHz offset from the

carrier but significantly degrades close-in performance compared to commercial available signal sources. Moreover, significant levels of side modes exists that are due to resonance conditions associated with the 9.166km delay lines. These side-modes degrades the timing jitters of the oscillator, even though there are reduced close-in to carrier phase noise.
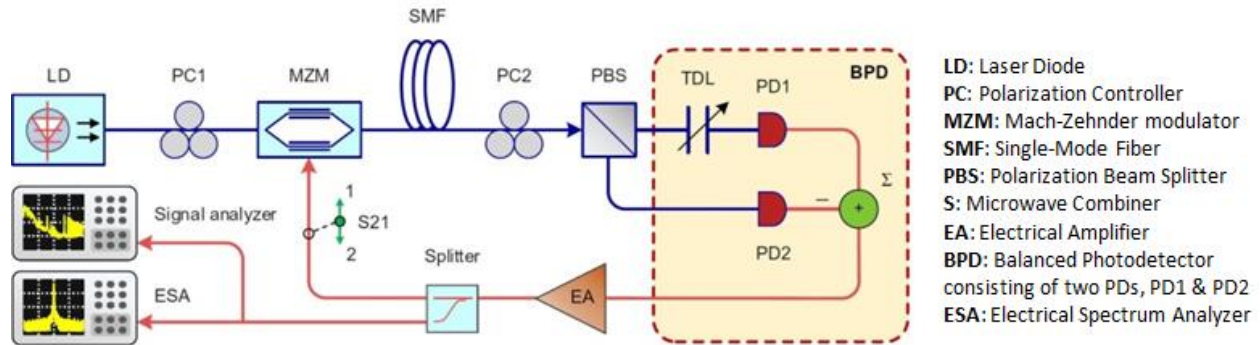

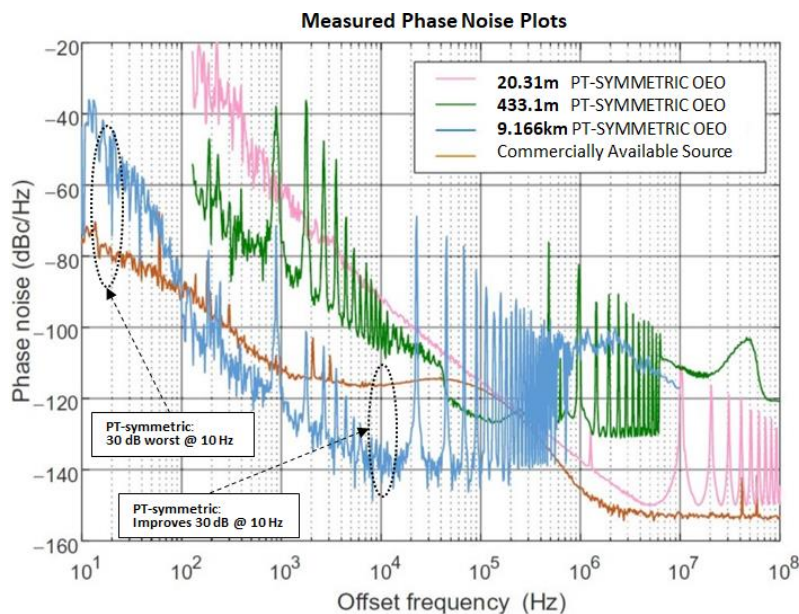Figure 4: Block diagram of the PT-symmetric OEO [8]

Fig.5: Compares the phase noise plots of PT-Symmetric OEO and commercial available source operating at 9.76 GHz [8]

The suggested methods to mitigate the poor close-in phase noise performances in PT-Symmetric OEO is to incorporate polarization-insensitive optical power splitter and electrical feedback loop to detect the phase and polarization changes, and perform real-time dynamic compensations. The recommended techniques can partially improve the close-in phase noise performance, while far away offset (>10 kHz) suffers degradation as well as lacks the broadband tunability. The current and later generation of communication systems demand high frequency signal sources with large frequency tuning features to meet the criteria for broad bandwidth and high data transmission rate. The research work carried out at Synergy Microwave Corp. New Jersey and Drexel University, Philadelphia lead to promising solutions based on forced SILDPIL techniques.

1.1 SILDPLL (self-injection locking double phase locking) OEO Synthesizers

Oscillator phase noise reduction can be achieved by forcing free-running oscillator using injection locking (IL) [9] and phase locked loop (PLL) [10]. While IL technique are easy to implement, the phase noise in the close-in offset frequencies is degraded due to frequency detuning and limited locking range as explained in [11]. On the other hand, the high gain loop filter enables the PLL to remove the close-in phase noise significantly, while far away offsets suffer from a higher noise. Sturzbecher *et al*. demonstrated that in externally forced oscillators, a better phase noise characteristics for both close-in and far-away offset frequencies and a wider locking range are achieved by combining IL and PLL (ILPLL) [12]. However, external reference sources are required in the conventional ILPLL topology, which limits the ultimate phase noise performance.

To bypass limitations imposed by an extremely stable external reference requirement, self-injection locking (SIL) [13] and self-phase locked loop (SPLL) [14] have been proposed. SIL and SPLL are essentially feedback control loops where part of the output signal is delayed and used as reference signal, thus eliminating the need for an external reference. The loop gain can be greatly enhanced in SILPLL as opposed to SIL or SPLL alone, thus providing more phase noise reduction.

For a long fiber delays, a large number of closely spaced side modes ($\Delta fL=200kHz.km/L$, where L is fiber length in km, as also seen in Fig (5) are expected in the forced oscillator spectra; therefore, multiple feedback paths are introduced to cancel these side modes by using SILPLL, SILDPLL, and SILTPLL depending upon requirement of side mode suppressions and corresponding timing jitters.

Figure (6) shows the block diagram of SILDPLL OEO synthesizer, uses SIL and double-sideband PLL techniques to minimize the phase noise at close-in and far out from the carrier. As shown in Figure (6), low RIN fiber laser (TWL-C-HP-M) is used to provide wavelength tunable laser signal. The signal transmits through optical fiber to create the delay line and then received by photodetector (DSC50S) to set signal pass through narrow band filter. Narrow band filter is the core of the OEO, which is use to select the oscillation frequency. In this research work, tunable YIG filter is used for wideband operations and coarse tuning of the frequency synthesizer. Further improvement is achieved by incorporating a narrowband optical transversal filter realized by using chirped fiber Bragg grating (CFBG) [15-18], where this optical transversal filter provides narrowband microwave signal filtering. Moreover, the optical transversal filter is wavelength dependent and provides frequency tuning as wavelength of fiber laser is tuned within pm. Beside the optical frequency selectivity of YIG and optical transversal filter, self-injection locking [14], self-phase locking [15] and their combination SILPLL [19] is also applied to provide reduction for synthesizer phase noise in both close in and far away to the carrier frequency. The block diagram outside the dotted square depicts SIL and DSPLL [20-21] simultaneously. There are two paths for modulated signal after MZM, one transmits the main loop of OEO and the other loop is split into two using as 3 km and 8 km dual phase locking signal. The combined phase locking signal is then inputted to a custom design 'Mixer+LPFA' board (block in Fig. 7). A double balanced mixer is integrated on this board with a low pass filter amplifier (realized using Op-Amp circuits) to work as phase detector and low pass portion of the PLL. The phase error of the OEO main loop is compared with the dual delay lines of the phase locking loop and the phase error signal is fed back to the bias port of MZM. Self-Injection locking signal takes the advantage of phase lock loop path and share the same 3km fiber using in SPLL path. Dual delay lines of 5km and 8km provides significant side-mode suppression. The 5 km SIL signal is tapped from one PLL signal and directly injected into the power combiner. The injected power level is expressed as $\rho=\sqrt{P_i}/P_o$, with P_i, the injected signal power and P_o, the OEO power level. The novelty of this paper is design, implementation, and testing of high frequency resolution 19" rack-mountable X-band and K-band frequency synthesizer using SILDPLL OEO. The high resolution tuning is due to fine tuning of an optical transversal filter using a chirped fiber Bragg grating (CFBG) as dispersive component for narrowband filtering. Second harmonic [22] generation is achieved by biasing of the DD-MZM close to V_π to generate half rectified optical pulses. 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 minutes with a maximum frequency drift of 4kHz.
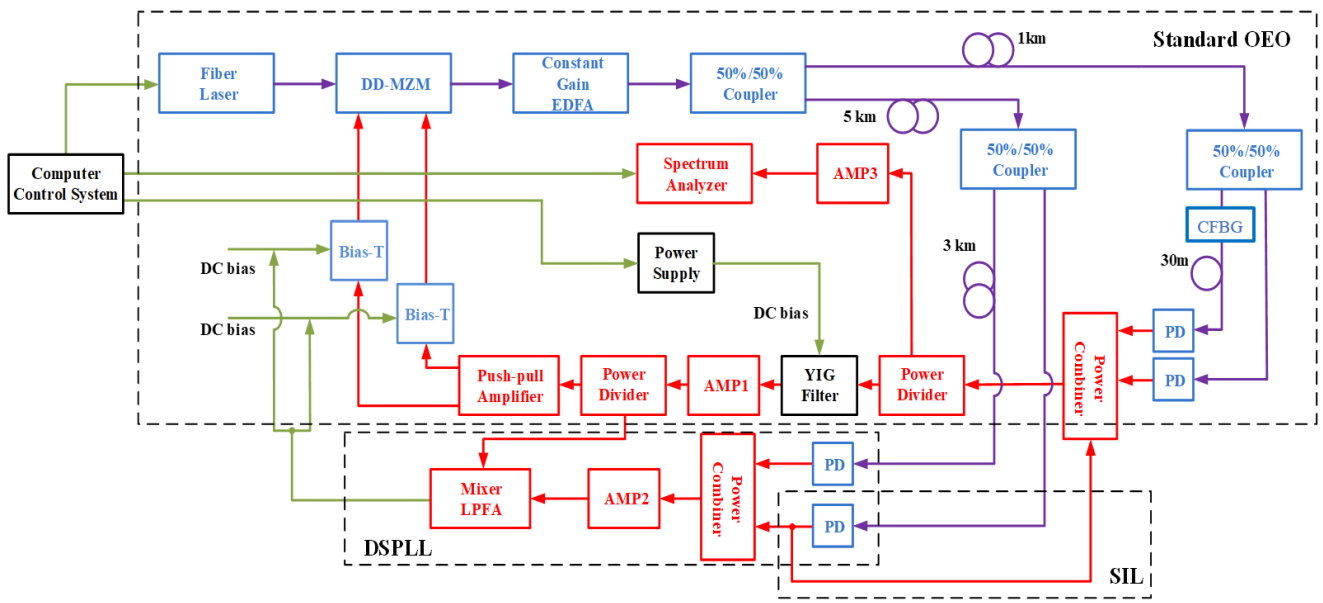

Fig.6. Block diagram SILDPLL Synthesizer system

1.2 Design Implementation SILDPLL OEO Synthesizers

The frequency synthesizer block diagram depicted in Figure (6) and hardware in Figure (7), utilizes SIL and double-sideband PLL techniques simultaneously, with multiple signal paths within the synthesizers in support of enhanced signal stability as well as application of modulation as needed.
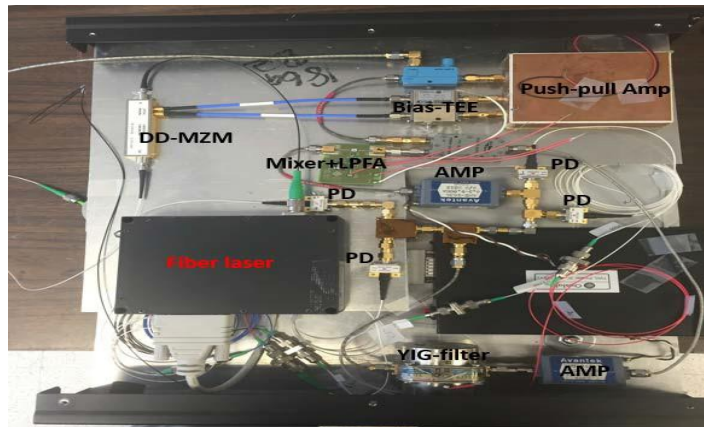
(a)　　　　　　　　　　　　　　　　　　　　　　　(b)

Fig. 7 shows the images of the X/K-band SILDIL OEO Synthesizer: (a) top view, and (b) front view

As shown in Figures (6) and (7), signals are combined within the synthesizer with the aid of a custom-designed double-balanced frequency mixer and lowpass-filter-amplifier (LPFA) assembly. The synthesizer design also incorporates operational-amplifier (opamp) circuits that work as phase detector and lowpass portion of the PLL. The high resolution and wavelength-sensitive tuning is due to the fine tuning made possible by the wavelength control of the fiber laser used as the optical source for the extremely narrowband optical transversal filter. The optical filter uses a chirped fiber Bragg grating (CFBG) as a dispersive component to achieve narrowband filtering. A current-tuned YIG filter is used in cascade along with the optical filter and CFBG to provide coarse frequency tuning across wide tuning ranges of X- and K-band frequencies. At X-band frequencies from 8 to 12 GHz, for example, the YIG filter tunes with a response of about 25 MHz/mA. Since the resolution of the current supply feeding the YIG filter is about 1 mA, the effective frequency tuning resolution of the YIG filter is 25 MHz. This combination of optical and electronic technologies results in relatively wide frequency tuning ranges with outstanding phase noise, both close in and far from the carrier. A higher frequency tuning resolution and narrowband filtering is achieved by dispersive CFBG based transversal filter as opposed to fiber based [23]. Figure (8) shows the phase noise measurement setup for the synthesizer. As shown in Figure (8), Agilent E3631A is used adjusted in constant current mode for tuning the YIG filter and Rohde & Schwarz FSWP is sued for phase noise measurement. At X-band, for example, the single-sideband phase noise is -110dBc/Hz offset 1 kHz from the carrier and -137dBc/Hz offset 10 kHz from the carrier for carrier frequencies from 8 to 12 GHz. In the time domain, this translates to 4.395 fs measured at side mode markers of 35 and 200 kHz from the carrier. At higher, K-band frequencies, the SSB phase noise is -103dBc/Hz offset 1 kHz from the carrier and -128dBc/Hz offset 10 kHz from the carrier or full operation of 16-24GHz, or time-domain response of 6.961 fs measured at side mode markers of 35 and 200 kHz from the carrier. The overall system for demonstration purpose is implemented into 19'' rack mount system for portable use, the size can be reduced depending upon applications. Figure (9) shows the phase noise plots for X and K band synthesizer for different fiber lengths.

Fig. 8: shows the Rohde & Schwarz FWSP phase noise measurement setup, SILDPIL OEO synthesizer in 19-in. rack-mount enclosure for portability, the size can be reduced based on applications
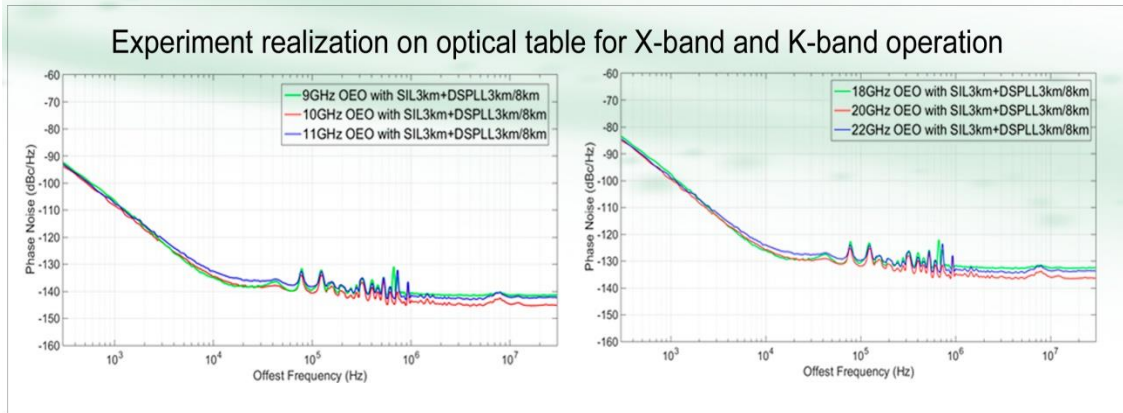
Fig. 9 Measured phase noise of X and K-band OEO in a 19" rack-mountable box shown in Figure (7)

In terms of size and power, the YIG filter is the dominant component in these optoelectronically driven frequency synthesizers. The main current consumption in the frequency synthesizer assembly takes place due to the YIG filter, which draws 150 mA at +10 V dc and about 1.5 W power. The amplifier, with two channels, draws 80 to 160 mA currents at +10 V dc and as much as 1.6 W power. The mixer LPFA, which uses a combination of frequency translation and filtering to extract the RF/microwave signals from higher-frequency optical signals, draws about 60 + 5 + 45 mA or 110 mA current, from respective supplies of +15, +5, and -5 V dc.

In stark contrast, the photodetector used in the frequency synthesizer operates at very low current and power, with its three cells each drawing about 10 mA current or 30 mA current at +5 V dc and about 0.15 W power as part of the frequency synthesizer dominated in terms of size and power by the YIG filter. The broadband dual-channel amplifier draws roughly 80 mA current per channel or 160 mA current from a +10-V dc supply, or about 1.6 W total power as part of the frequency synthesizer.

2. Monolithically IOEO (Integrated Optoelectronic Oscillator

Recently, Tang et. al [24] demonstrated integrated OEO shown in Figure (10), both the optical part and electrical part are packaged on a print circuit board (PCB) within size of 5×6 cm^2. The measured phase noise for oscillation frequency 7.30 GHz is −91 dBc/Hz@1MHz for the injection current at 44 mA. The reported integrated solution is not attractive because of limited tuning and poor phase noise performance due to high relative intensity noise (RIN) of the DML. Since the temperature control of the laser is really hard to realize on chip, the large RIN worsen the phase noise.
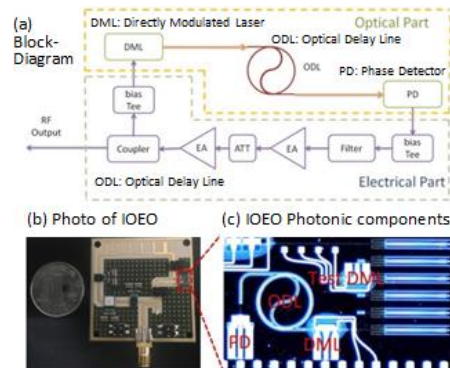

Fig. 10 shows the IOEO: (a) Block-Diagram, (b) Photo of the IOEO, (c) Photonic components of the IOEO

In this research work, integrated topologies using monolithic fabrication that are compatible with Si-Photonics are explored to reduce size and cost while temperature sensitivity is also to be improved.

Chip level multi-mode laser generates beat-note at radio frequencies [25], but those suffer from a very poor phase noise characteristics. Fully integrated topologies using monolithic fabrication that are compatible with heterogeneous Si-Photonics are explored to reduce size and cost while temperature sensitivity is also to be improved. The block diagram showed in Figure (11) provides the laser configuration, consists of 4 major sections [26] including distributed Bragg reflector (DBR), gain medium, phase tuning section and electro-absorption modulator. Distributed Bragg reflector is used as a filter to select laser output frequency [27]. Phase tuning section [28] in the laser set up works for the frequency tuning. It works as the phase modulator in the DBR laser. Different DC bias voltages applied to drive different output frequency

from each multi-mode laser [26]. The output Y-junction provides input to a high speed photodetector for efficient detection of the ultra-stable beat-notes RF signal. Gain medium part is designed using InGaAsP-InAsP multi quantum well structure for operation at about 1550 nm, where a threshold current of about 30 mA is estimated. The research work is in progress for the fabrication of these designs to monolithically integrated components using designs that match with any   of heterogeneously integrated Si-Photonics foundries [30].
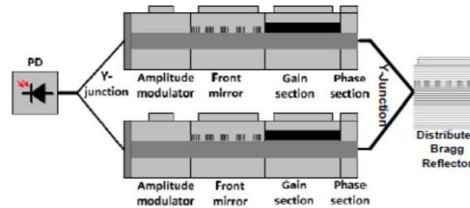

Fig. 11 Block diagram of RF beat-notes generation laser system using DBR based multi-modes laser pairs [26].

Conclusions

The reported SILDPIL OEO synthesizer in 19" rack-mount enclosure is built on patented techniques [18-19] for portability, the size can be reduced based on applications and requirement. For detailed information and availability of the OEO synthesizer box operating at different frequencies, readers are encouraged to contact authors (Prof. Afshin Daryoush, Email: daryousa@drexel.edu; Prof. Dr. Ing. Habil Ulrich L. Rohde, Email: ulr@synergymwave.com). The further research work is in progress for monolithic integrated solution aims at the design and implementation of hybrid optoelectronic systems by combining the integrated microwave and the photonics circuits on chip. The recent development of different photonics integration material platforms, including Silicon on Insulator (SOI), Indium Phosphide (InP) and Silicon Nitride (Si_3N_4), opens the prospective way for the potential of integrating an OEO on chip targeting for 5G applications.

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