Compact and Highly Stable Frequency Synthesizers for Integrated RF Front-Ends

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Intermodal oscillation of multimode InGaAs/InP lasers at X-Band frequencies are stabilized using self-forced oscillation of self-injection-locked, triple-phase-locked loop (SILTPLL), self-mode-locking (SML) and a combination of SML and SILTPLL. As the number of SML modes are increased, lower phase noise close to the carrier is measured. With 201 modes with intermodal oscillation frequency of 10 GHz, a phase noise of -157 dBc/Hz at 10 kHz offset from a 10 GHz carrier is predicted, while any random phase error among self-mode-locked modes can be corrected using a self-forced oscillation technique. A compact realization is feasible using a heterogeneously integrated InP multimode laser (MML) on Si photonics, using low loss SiN resonators as delay elements and SiGe low noise RF electronics.

Low phase noise RF sources are important elements of coherent detection in many RF applications, such as terrestrial and space communications. One of the key technological challenges faced by efficient front-end electronics for reconfigurable wireless communication, sensitive electronic warfare, jamming resistant radar and diversified remote sensing systems is reliance on highly stabilized local oscillator frequency sources. The traditional method of generating stable RF signals by multiplying the frequency of a highly stable crystal oscillator[1] suffers from high power consumption, large size, poor AM noise and high AM-to-PM noise conversion, compared with forced oscillation techniques such as injection locking and phase-locked loops.[2] Alternatively, an optoelectronic oscillator has been developed and reported for X- and K-Band with a frequency resolution better than 50 kHz and phase noise better than -130 dBc/Hz at 10 kHz offset from the carrier.[3–5] A single chip design minimizes the environmental impact of temperature, vibration and radiation that influences long-term frequency stability. A small IC is preferred over its commercial 19 in. rack-mountable frequency synthesizer counterpart because of its smaller size, weight, power consumption and lower cost.

This article describes a compact chip-level integration using the intermodal output of a multimode semiconductor laser in the tens of GHz. While its performance using different frequency stabilization methods is reported elsewhere,[6-8] its salient points are reviewed here to provide an overview of the single chip design.

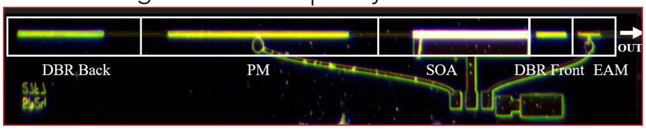


Fig. 1 **Fabricated DBR-based multi-mode, multi-section, semiconductor laser on a 0.8 mm x 4.6 mm InP chip.**

MML AS AN RF SOURCE

A distributed Bragg reflector (DBR) multimode, multi-section semiconductor laser for RF generation is shown in ***Figure 1***. It has no external reference and uses optical components fabricated with an InP process from the SmartPhotonics foundry.[9] The device has four major sections: semiconductor optical amplifier (SOA) for gain, phase modulator (PM) for RF frequency tuning, filtering DBR for lasing function at select wavelengths, and electro-absorption modulator (EAM) for mode number control using multi-quantum well InGaAs/InP for multi-mode laser (MML) operation at 1550 nm with intermodal RF signal of tens of GHz. The lengths of the DBR back and front mirrors are 600 and 200 µm, respectively, the phase section length is 1250 µm and the SOA length is 800 µm. To form the complete laser cavity, the sections are connected by shallow-etched waveguide. The total cavity length, including the connecting waveguide of approximately 4,000 µm, yields an intermodal oscillation frequency of about 11.5 GHz for multiple modes over the 80 GHz gain spectrum of the SOA. The external EAM, 200 µm long, is used to selectively suppress various modes. Electrical connections are placed on the chip to provide DC bias for the operation control of SOA, PM and EAM. A via connects the ground pad to the backside of the chip.

The microchip is mounted on a temperature-controlled surface (see ***Figure 2***) for static and dynamic characterization of MML in a constant temperature. A copper sheet placed under the microchip and mounted on a Peltier cooler maintains 20°C throughout testing, using a thermistor and temperature controller maintaining the fluctuation to ±0.2°C. Mechanical probe stations provide electrical microprobes for the DC and RF input and the optical lensed fiber holder to collect the optical output. The optical output is monitored with an optical spectrum analyzer (OSA) through the lensed fiber optical coupler and photodiode. Its dynamic modulation has an important role in the phase-locking process of RF signals with greater than 50 MHz bandwidth. Intermodal oscillations are detected using an external high speed photodetector and displayed on an RF phase noise analyzer.

The EAM section controls the laser modes by shifting the quantum-confined Stark absorption edge. PM and EAM bias were initially set at 0 V, and the measured test of the integrated laser showed five dominant modes on the OSA. The fundamental mode was around -12 dBm at 1550.85 nm when the SOA injection current was 80 mA. The mode gap between each mode was around 11.5 GHz, which correlates with the estimated effective cavity length of 13.065 mm. The free-running intermodal output was around 11.5 GHz with about -10.6 dBm power at 11.5496 GHz. Poor phase noise of -5 dBc/Hz at 1 kHz offset from the carrier and -30 dBc/Hz at 10 kHz offset was recorded, as well as a 30 MHz center frequency shift over 10 minutes. Timing jitter was estimated to be 266.1 ps for 1 kHz to 1 MHz offset frequencies, before significant reduction using self-forced oscillation techniques.

The intermodal RF frequency is tuned when a DC injection voltage is applied to the PM section (shown in Figure 1). An applied bias from -5.0 to 0 V to the PM section changes the index of refraction in the optical waveguide and the effective laser cavity length, causing a shift in the intermodal oscillation frequency. The phase section tuning sensitivity

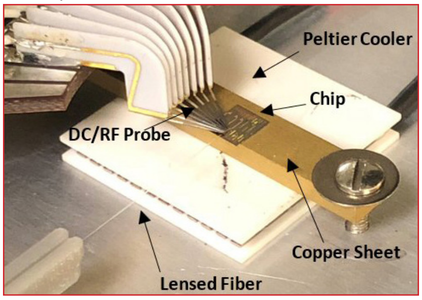


Fig. 2 DBR-based multi-mode multi-section semiconductor laser test environment.

was measured at several PM biases; greater than 700 MHz tuning at X-Band was achieved with an average frequency tuning sensitivity of approximately 150 MHz/V. Compared to other techniques, this tuning range and sensitivity performance is among the best reported since its tuning sensitivity is significantly better than that of conventional RF voltage-controlled oscillators (VCO).[10]

Novel forced oscillation techniques of self-injection locking[11] (SIL) and self-phase-locking loops[12] (SPLL) were used to improve the stability of the intermodal oscillation frequency. An optimized delay line using self-injection locked triple phase-lock loop (SILTPLL)[13] improves the phase noise performance without any external reference.

MML SILPLL STABILIZATION

To improve the stability of the free-running oscillation frequency, forced oscillation was employed. When a stable source is available, frequency stabilization using an external frequency reference has been reported by Daryoush et al.[14] However, self-forced oscillation techniques are useful when constructing a clean frequency source[2] as an external reference to stabilize distributed oscillators.[15]

Referring to ***Figure 3***, the conceptual block diagram of a self-injection-locked phase-locked loop (SILPLL)[11] using a control theory representation is shown by the injection locking loop with the G_{IL} path. A portion of the oscillator output signal is delayed by a long delay (τ_d) and fed back to the oscillator with coupling factor ρ. The phase of the delayed signal is compared to the instantaneous phase of current signal to generate an error signal for self-injection. The phase noise of the self-injection locking system at offset angular frequency of ω_m is expressed by equation (1):[11]

$$\left|S_{SIL}(\omega_m)\right| = \left|H_{SIL}(S)\right|^2 S_{n_i}(\omega_m) + \left|HE_{SIL}(S)\right|^2 S_{n_o}(\omega_m) \quad (1)$$

where in Laplace space of $S = j\omega_m$

$$H_{SIL}(S) = \frac{G_{IL}}{\left(1-e^{-s\tau_d}\right)G_{IL}+1}$$ and

$$HE_{SIL}(S) = \frac{1}{\left(1-e^{-s\tau_d}\right)G_{IL}+1}$$

In equation 1, S_{ni} and S_{n0} are the residual noise of the system and the phase noise of the oscillator, respectively. When the gain of the feedback system is suffice, the phase noise introduced by the free-running oscillator is to be significantly reduced.

The concept of self-phase-locking[12] is also shown in Figure 3, i.e., the loop with the G_{PLL} path. In the self-phase-lock loop (SPLL) process, a portion of the oscillator output is delayed, and the phase of the delayed signal is compared to the phase of the current signal. The comparison signal is amplified by an operational amplifier and fed back to the VCO tuning port (e.g., the voltage control of PM portion of the MML). The feedback frequency control is initially a low frequency signal of up to 30 MHz and eventually settles at a DC signal when no frequency error is detected between the delayed and non-delayed signals.

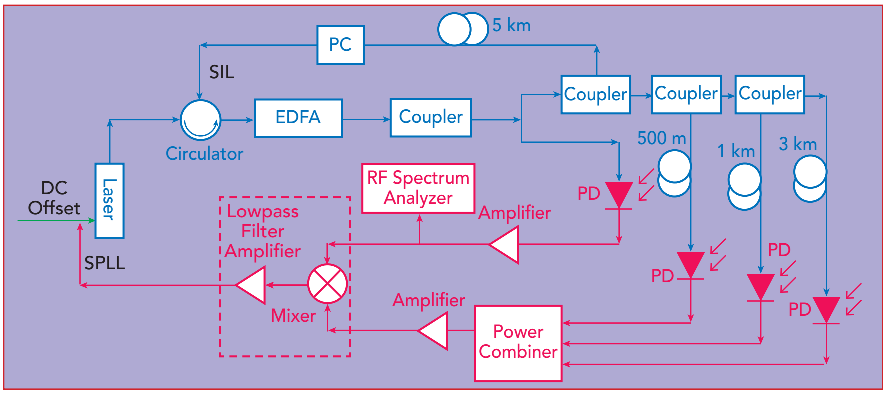


Fig. 4 Inter-modal oscillation stabilization using SIL and triple self-phase lock loop (TSPLL).

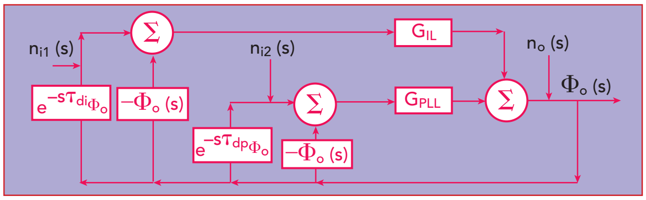


Fig. 3 Control theory representation of a SILPLL[16] composed of a SIL[11] with time delay of τ_{di} and a SPLL[12] with time delay of τ_{dp}.

With the principal of superposition applied, the overall noise of the SPLL system is[12]

$$S_{SPLL}(\omega_m) = |H_{SPLL}(S)|^2 S_{n_i}(\omega_m) + |HE_{SPLL}(S)|^2 S_{n_o}(\omega_m)$$

where

$$H_{SPLL}(S) = \frac{G_{PLL}}{\left(1-e^{-s\tau_d}\right)G_{PLL}+1} \text{ and}$$

$$HE_{SPLL}(S) = \frac{1}{\left(1-e^{-s\tau_d}\right)G_{PLL}+1} \quad (2)$$

Combining the SIL and SPLL leads to the SILPLL with a similar simplified expression,[16] conceptually shown in Figure 3. In this topology, the SIL and SPLL operate at the same time with separate external delay circuits. The derived expression using superposition is

$$S_{\phi_o} = \left|\frac{G_{IL+}G_{PLL}}{1+K_{IL}G_{IL}+K_{PLL}G_{PLL}}\right|^2 S_{n_i} + \left|\frac{1}{1+K_{IL}G_{IL}+K_{PLL}G_{PLL}}\right|^2 S_{n_o}$$

where

$$K_{IL} = 1-e^{-s\tau_{di}},\ K_{PLL} = 1-e^{-s\tau_{dp}} \quad (3)$$

Equation 3 signifies that the SIL, SPLL and their combination significantly reduce the phase noise without any external reference.

The setup to test the SIL is shown in ***Figure 4***, where the instantaneous laser output is amplified using a constant gain, erbium-doped fiber amplifier (EDFA). The output is delayed by 25 µs using a 5 km fiber and fed back to the laser through an optical circulator. A tunable optical attenuator placed before the optical circulator port enables the dynamic performance to be evaluated by adjusting the optical injection power level. A

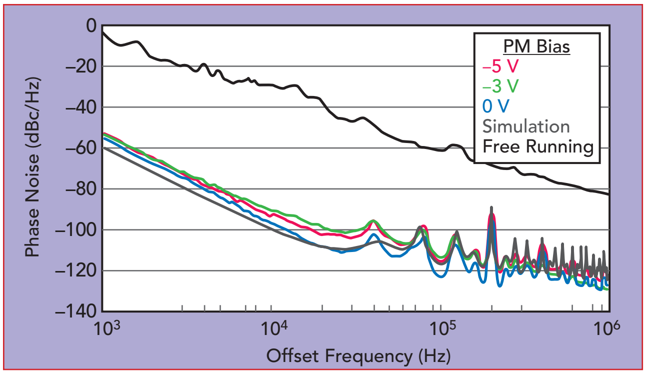


Fig. 5 Simulated vs. measured phase noise of self-forced SILPLL-stabilized inter-modal MML oscillator vs. bias. SIL: 5 km, STPLL: 500 m/1 km/ 3 km. Carrier frequency = 11.54 GHz, 3.59 dBm output. Free running oscillator shown for comparison.

polarization controller after the optical delay line provides a high efficiency optical injection signal to the optical waveguide.

The performance parameters of phase locking range and time to pull-in to phase locking state[17] for the SPLL is enhanced when SIL is incorporated to SPLL. The delayed and non-delayed signals are simultaneously compared in a phase detector that is realized using a mixer and lowpass filter amplifier (see Figure 4). Any instantaneous low frequency phase error pulls the frequency deviation back to the original RF oscillation phase-locking using the PM section of the MML. The PLL loop bandwidth of 50 MHz was selected to completely cover 30 MHz of frequency drift. Different offset bias conditions of the PM section were compared using optimized self-injection locking 5 km and triple, self-phase-locking 0.5, 1 and 3 km delay lines to test the phase noise (see ***Figure 5***). Triple non-harmonically related delay loops[16] suppress the peaks of the side modes from -30 to -90 dBc. In the best scenario, the timing jitter was 0.448 ps, 600× better than the free-running jitter. The accuracy of self-forced oscillation modeling results are validated and experimentally reported for phase noise of both DRO[11-14] and optoelectronic oscillators.[4]

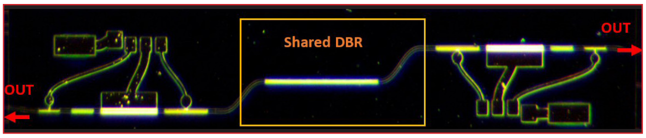


Fig. 6 Shared DBR-based multimode semiconductor laser with symmetric multi-section multimode lasers on the left and right of a shared DBR. Chip dimensions = 4.6 mm x 1.2 mm.

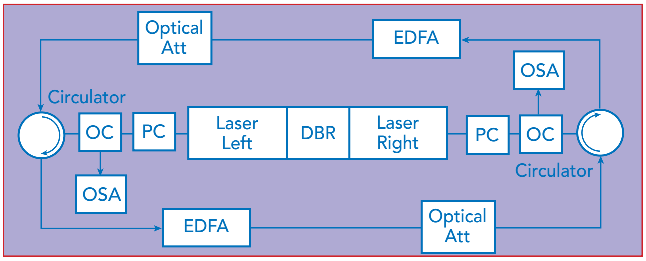


Fig. 7 SML method with two counter-propagating feedback waves of symmetric laser pairs. The current realization uses modular components off the InP chip.

FREQUENCY SYNTHESIS USING SML

To achieve broadband frequency synthesis, two MML pairs (see Figure 1) were configured to produce counter-propagating laser light feedback to form an RF synthesizer (see ***Figure 6***). This SML process[7] combined with frequency detuning the multimode laser sections easily provides tunable RF beat notes. ***Figure 7*** shows a block diagram of this novel SML method, which does not rely on standard active mode-locking where an external frequency reference is required. The symmetric outputs of multi-section laser pairs interact as two counter-propagating feedback waves. The larger the number of modes locked to one another, the lower the close-in phase noise, i.e., the better the RF frequency stability.[7,8]

The SML technique forces one laser output to be coherent with the other by locking the overlapped modes of the counter-propagating lasers, as bias currents of the SOA and voltages of the PM and EAM are tuned through the shared DBR and added external feedback. As shown in Figure 7, the amplified outputs from the left and right lasers are coupled back to the

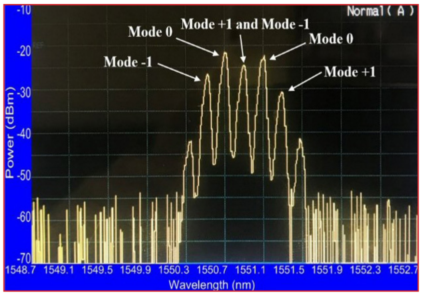


Fig. 8 Five modes shown on an optical spectral analyzer.

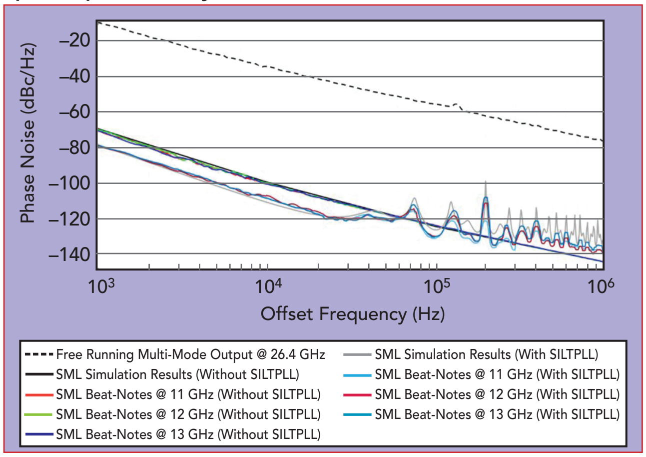


Fig. 9 Phase noise for beat-notes at 11, 12 and 13 GHz with five self-mode locked modes,[7] with and without the SILTPLL.[8] Measured and modeled results reported by Sun also shown.[18]

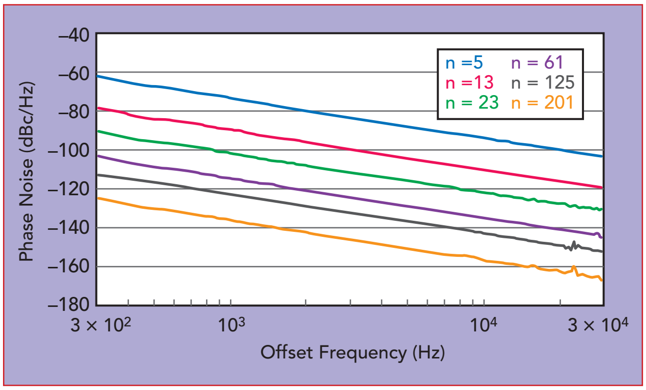
opposite lasers through optical circulators. The optimum level of light coupling is quantified by feedback power levels (e.g., an EDFA with optical attenuator). The measured fundamental mode of the two lasers with their intermodal gap is approximately 2.1 Ao (i.e., 26.4 GHz) for each laser. The spectra of the correlated modes is shown in ***Figure 8***. Mode +1 of the left laser overlaps with mode -1 of the right laser, which provides exactly five modes that are correlated. The best interaction of five locked modes of intermodal oscillations at 26.4 GHz achieves a measured phase noise of -92 dBc/Hz at 10 kHz offset, which is a 55 dB improvement compared to the free-running case. The estimated timing jitter is 72 fs, 1000× lower than the estimated 70 ps for the free-running case over a bandwidth of 1 kHz to 1 MHz.

To achieve RF frequency synthesis, continuous wavelength tuning of the laser section is used after achieving mode-locked status, by tuning the SOA and PM to produce different beat notes. During this process, the laser modes remain locked. By tuning each laser section, the intermodal oscillation frequencies are tuned to 11, 12 and 13 GHz with RF power levels of 4.79, 4.80 and 4.70 dBm, respectively. The related phase noise and a comparison to analytical modeling are shown in ***Figure 9***.

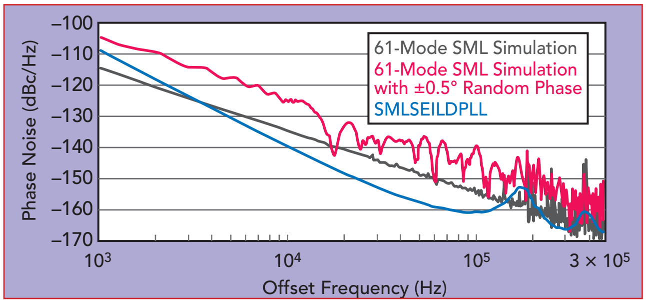
COMPACT X-BAND SYNTHESIZER

The intermodal oscillation frequency of a MML can be further stabilized for a frequency synthesizer by combining self-forced-oscillation and SML. The phase noise comparison is shown in Figure 9, where the self-mode-locked modes are frequency tuned and employ a SILTPLL to reduce the phase noise by an additional 10 dB at offset frequencies below 100 kHz.

This improvement is attractive to realize highly stable synthesizers. The US defense advanced research project agency (DARPA) has recently challenged the RF synthesizer community with the following performance requirements under the GRYPHON Program:[19] stable frequency synthesis from 1 to 40 GHz packaged in under 10 cm^3, with phase noise no greater than -150 dBc/Hz at 10 kHz offset from a 10 GHz carrier with a 6 dB/octave roll-off, and the capability to operate in a harsh military environment (-40°C to +85°C temperature range and 40 g vibration). DARPA's design challenge can be met using the unique features of the MML: 1) the intermodal oscillation frequency can be modified by adjusting the common DBR section length while optimizing the multiple quantum well structure by increasing SOA gain, phase modulation sensitivity and effective cavity length; 2) the optical fiber delay elements can be replaced with cascaded, high-quality factor resonators.[20-23] Increasing the cavity length and DBR bandwidth accommodates a large number of



▲ Fig. 10 Phase noise vs. MML mode number. With 201 modes, the phase noise is –156 dBc/Hz at 10 kHz offset from a 10 GHz carrier.



▲ Fig. 11 Simulated performance of a 61-mode MML SML, SML with ±0.5 degree random phase error and corrected using SEILDPLL (delays of 5 ms for SEIL and 5 µs and 15 µs for SDPLL with ±0.5 degree phase error SML).

modes for the MML. ***Figure 10*** compares the close-in phase noise of the SML as the mode number increases from 5 to 201, showing a significant reduction in phase noise, which achieves the performance requirements of the Gryphon program.

As the number of modes increases, phase-locking using SML becomes more sensitive to any internal phase degradation. Referring to ***Figure 11***, note the simulated performance comparison of 61 modes of SML with no phase error and the case with ±0.5 degree of random phase error, where the phase noise degrades by 10 dB. However, when the self-electrical-injection locking and dual self-phase-locked loops (SEILDPLL) is introduced with random phase error using fiber delays of 1 and 3 km, phase noise of -140 dBc/Hz at 10 kHz offset from the carrier is achieved. Similar performance is predicted for cases of a self-forced MML with mode numbers larger than 61. These cases indicate the utility of SML and SEILDPLL to improve the stability of free-running intermodal oscillators to 40 GHz.

To meet DARPA's 10 cm^3 package size, the suggested approach incorporates a heterogeneously integrated InP MML with optical delay elements fabricated with silicon photonics (SiP). A conceptual block diagram is shown in ***Figure 12***, where SiP is used for the passive optical couplers and delay elements, combined with integrated electronics using a low phase noise SiGe RF amplifier, phase detector and loop-filter amplifier as part of the SEILPLL. The green dotted line encloses the InP material heterogeneously mounted on a Si substrate. The black rectangle includes the SiP chip and the overall assembly is outlined in purple. The optical delay elements are realized using high-quality micro-disk resonators.

CONCLUSION

Optoelectronic techniques are quite viable for implementing high stability microwave frequency synthesizers. Significant improvement in frequency stability is attained using custom designed modular implementation of OEO based on self-forced oscillation technique of SILPLL.[3] To reduce size, integrated solutions of SILPLL[24] are considered by integrating low noise RFIC using SiGe technology with SiP based optical modulators.[25] Compact design of frequency synthesizer is demonstrated by employing InP based MML and intermodal oscillation frequency stabilization using concept of SML[26] combined with SILPLL using high Q compact resonators.[27] A combined design following the intellectual properties described here could potentially meet stringent requirements of the DARPA's GRYPHON Program, which has challenged the technical community, a compact RF synthesizer using a heterogeneously integrated InP MML chip on SiP is pro-

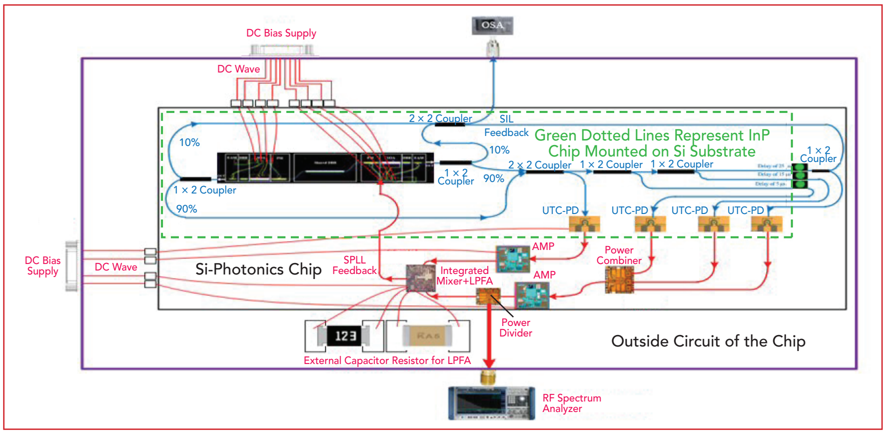


Fig. 12 **Conceptual block diagram of a forced oscillation, mode-locked, multi-mode laser synthesizer on a ~10 mm x ~4.2 mm silicon chip.**

posed that will provide 1) low phase noise (-150 dBc/Hz at 10 kHz offset from a 10 GHz carrier), 2) broadband tuning (1 to 40 GHz), 3) small size (≤ 10 cm^3) and 4) operation in a rugged environment (-40°C to +85°C temperature range and 40 g vibration). A compact RF synthesizer with a very low phase noise in microwave frequency range could be envisioned by relying on the self-mode locking of a large number of modes of the presented multi-mode laser with a tunable intermodal RF frequency. Addition of self-forced oscillation technique assures low phase noise of RF signal over the challenging environments.■

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