Narrow-Linewidth Microwave Generation by Optoelectronic Oscillator

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***Abstract*—The use of optoelectronic oscillators (OEOs) has increased to a large extent in the recent decade. This paper discusses OEO based on a 1.55 µm direct-modulated square microcavity laser which is used to produce a narrow-linewidth photonic microwave signal. Since the Q factor of OEO is very high, the quality of microwave signals is reported to be very high. Through the course of the report, we will touch upon the square microcavity laser and its uses as a direct electro-optic modulator and the significance of low phase noise and the Q-factor for the generation of microwave signals. The experiment is performed over two types of architectures of OEO which are single-loop and dual-loop. The SSB phase noise has been discussed further for each type respectively. The narrow-linewidth was noted 30 Hz by the first harmonics of both loops. SMSR of 55 dB for the first harmonics and tunable microwave signals ranging from 1.85 to 10.24 GHz with low-phase noises.**

***Index Terms*—Optoelectronic Oscillator, Microcavity Laser, Direct Modulator, MMIC OEOs, Microwave Signal, Narrow Linewidth.**

I. Introduction

For a long time generation of the high-quality microwave, signals have been an important research field. Various methods have been proposed in the past decades to produce signals of low phase noise, narrow linewidth and a good tunable range. Traditional methods proposed were to obtain microwave signals such that they are spectrally pure. The use of either crystal oscillators or other schemes which includes non-linear electronic device based frequency multipliers. Along with these techniques photonics technology were also included such as optical injection, high-frequency comb generation, etc. The merits of the use of photonics technology were the free and low propagation loss of the electromagnetic waves in the devices. Among them, the Optoelectronic oscillator (OEO) was one of the techniques which were based on the optoelectronic feedback loop. The invention of the OEO in the year 1996 as a low phase microwave signal source by X. S. Yao and L. Maleki opened a new area of research and a lot of advancement was followed in the last two decades for being simple and cost-effective and thanks to the large Q-factor of the device along with the low optical delay line.

In the paper, we will discuss one of the applications of OEO which is narrow-linewidth generation. Since we mentioned that the Q-factor of OEO is very high, this implies that the bandwidth of the OEO has to be low enough to give us a large Q. Also, we can understand this by the way that Q-factor is a ratio of energy stored in the circuit/cavity and the amount of energy dissipated by the same system. Since the optical lines face low propagation loss as compared to the electronic oscillators and oscillator based on surface wave accoustics, OEO can be said to have a lead among them. Moreover, the phase noise degradation of the electronic devices is given by 20log10N in the case of the frequency multiplication process where N is the multiplication factor of the electronic devices

II. Structure And Operation

A typical OEO consists of a laser source which can be either a pulsed wave laser of a continuous wave laser. This laser is assembled along with the electro-optic modulator (EO Modulator), a fibre delay line that has to be long enough, a photodetector (PD), an optical amplifier along electronic

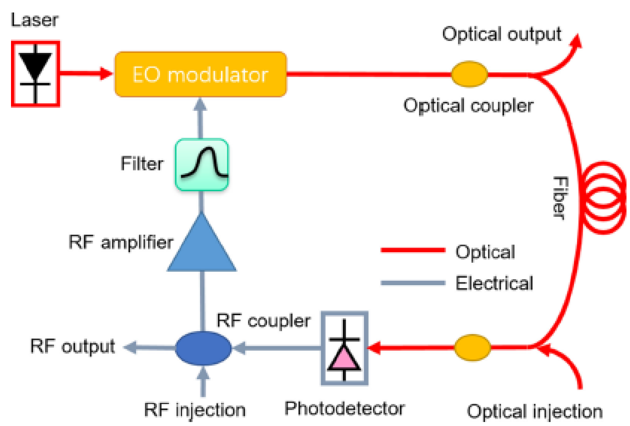

Fig. 1. Schematic of a typical Opto-electronic oscillator (OEO) for microwave signal generation.

devices such as an amplifier, phase shifter, and a bandpass filter. The principle of operation is when the gain is greater than the loss in the cavity, stable oscillation build-up with the help of noise. However, the centre frequency of oscillation is decided with the use of a bandpass filter (BPF). We shall use the continuous wave laser as per our requirement of the application of narrow linewidth generation.

A. Basic Operation of OEO

The light is obtained from the continuous wave laser which is injected into the electro-optic modulator. The laser light of very high frequency is modulated in the modulator along with the RF frequency which is obtained from the output of the BPF.

This modulated signal is passed to the optical delay line which is followed by the detection at the photodetector (PD). For the signal to sustain in the oscillator the loop gain has to exceed the total loss of the cavity along with the other important condition that the phase increments of the signals should be even multiples of 2π for a single circulation.

The modulation of the OEO can be expressed based on the input and output relationships of the voltage of the EO modulator such that $V_{in}(t)$ and V_{out} are represented respectively as

$$V_{out} = V_{ph}\left\{1 - nsin\pi\left[\frac{V_{in}(t)}{V_\pi} + \frac{V_B}{V_\pi}\right]\right\} \quad (1)$$

where V_{ph} is the voltage generated by the photon at the amplifier, n is the modulation index of the OEO such that it is related to the extinction ratio of the frequency modulation. V_π and V_B are the half-wave voltage and the bias voltage of the modulator.

B. SSB Phase Noise

After solving for the power spectrum density S_{RF} of the oscillation frequency, we obtain a sideband phase noise characteristics of OEO such as

$$S_{RF}(f) = \frac{4(\tau)^2}{(f)^2}, |\, f \,| << \Delta f_{FWHM}/2 \quad (2)$$

$$S_{RF}(f) = \frac{4(\tau)^2}{(f)^2}, |\, f \,| << \Delta f_{FWHM}/2 \quad (3)$$

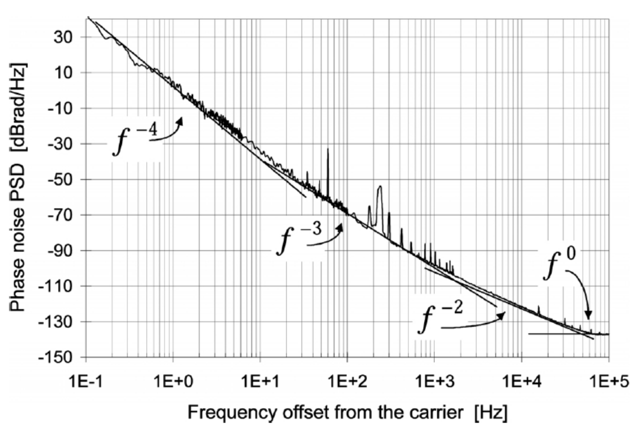

Fig. 2. Phase and frequency relation of a typical single loop OEO.

This explains that the power spectrum magnitude away from the full width half maximum (FWHM) starts decreasing with the frequency. The response of the phase noise power characteristics can be seen in the fig. against frequency. This characteristic makes the OEO more favourable to use since the phase noise of the device is decreasing as compared to the convention electrical oscillators where the phase noise is still significantly large. Moreover, the noise generated is independent of the frequency of oscillation in the cavity.

C. Q-Factor of OEO

Also, the Q factor for a single-loop OEO can be expressed as

$$Q = \frac{\omega_0\tau}{2}$$

Where τ represents the delay of the optical line, ω_0 is the frequency of the input RF signal. The dependence of the Q factor here is directly proportional to the delay of the optical line. In a more intuitive we can imply that the Energy stored within the device can proportional to the length of the optical length of the fibre. However, for longer optical fibre, there is more optical delay. To make a compact OEO we have to trade it with the Q factor which is going to have a direct effect on the quality of modulation and the RF signal being produced.

III. Components Of The OEO

A. Electro-Optic (EO) Modulator

The schematic of the OEO used in our paper is shown in the figure. The EO modulator is broadly classified into two types (1) Direct EO Modulator (2) External EO Modulator. In direct modulators, light from a laser diode is directly modulated by combining the electrical signal with the bias of the laser diode. Although this method is not very efficient, it is mainly used for short-distance data-communication due to its simplicity. For a high data rate with a large extinction ratio, external modulators are used. In this scheme, the laser operates on a constant bias producing a narrow linewidth continuous optical carrier. The data is encoded onto the optical carrier by the modulator, external to the laser cavity. In this paper, the use of a Direct EO modulator semiconductor laser for the optical injection is performed to reduce the RF loss and simplify the OEO system. For this, the use of various microcavity lasers can be proposed.

B. Square Microcavity Laser

The directly modulated semiconductor laser used in the OEO uses an AlGaInAs/InP square microcavity laser of 1.55 μm. The side length is reported to be 16 μm which is fabricated using

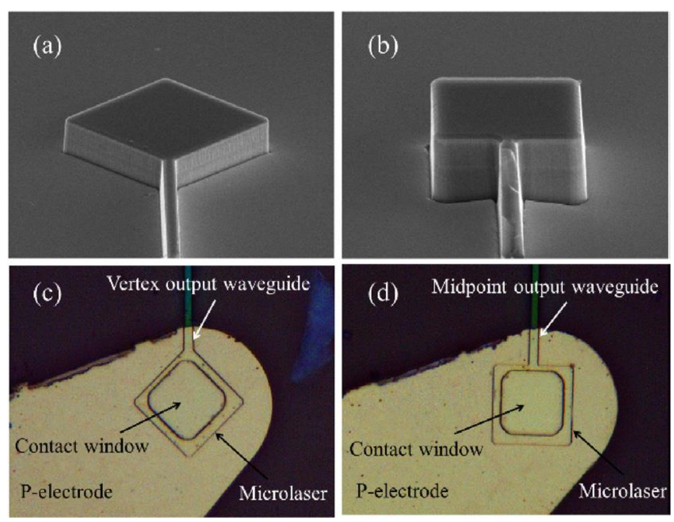

Fig. 3. SEM images for square microcavity lasers with output waveguide connected to (a) one vertex and (b) the midpoint, and microscopic images (c) one vertex and (d) the midpoint.

standard planar fabrication technology. The waveguide can be connected to the cavity either at the vertex or one of its sides. In this experiment performed the output waveguide is connected to a vertex of the cavity for the unidirectional emission of the laser. The Q-factor obtained by the respective square microcavity laser is nearly 10^5.

The EO Modulator and the LASER can be considered as the heart of the OEO. However, we shall also note down the remaining components of the schematic such as the use of a 20 GHz Electronic Network Analyser (ESA). The Bias T of 26.5 GHz was used to bias the laser with a DC voltage which acts as

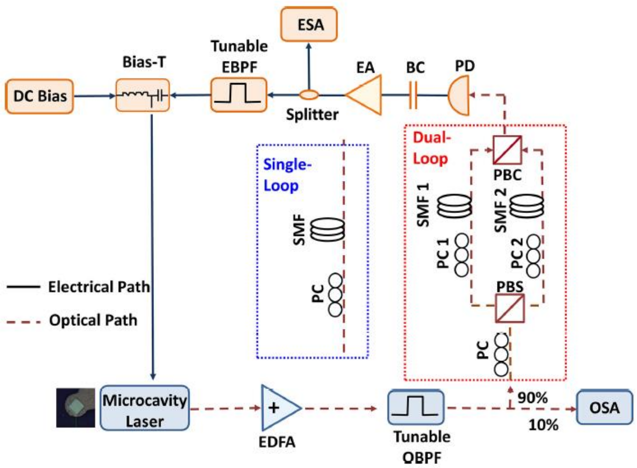

Fig. 4. Experimental setup for photonic microwave generation of Narrow-linewidth. The single-loop and Dual-loop OEO along with the other components of the schematics have been represented.

a pump for the laser source. The optical amplifier is one of the major components since the degradation of the optical signal in the loop can occur along with the splitting of the optical signal in the Optical Signal Analyser (OSA) along with the coupling losses. The optical amplifier here is the Erbium-Doped Fiber Amplifier (EDFA) which will maintain the gain of the loop. An OSA is used to monitor the light from the laser which utilizes 10% of the power. The remaining light is detected by a photodetector having a responsivity of 0.7 A/W. An optical bandpass filter is used for filtering out the background amplified noise and the rejection of undesired minor modes. The electrical signals are thereby amplified by 40 dB using an electrical amplifier to compensate for the RF loss in the electrical path. This is further followed by an electronic bandpass filter of bandwidth 50 MHz which is tunable in the range of 1.8 to 18 GHz to suppress the undesired frequency noise. In our case for the single loop architecture, the single-mode fibre (SMF) length is 2.5 km whereas for the dual-loop OEO the SMF lines have lengths of 3 and 2.5 km respectively.

IV. Microwave Generation Of OEO

The oscillations are generated with the help of a large modulation index of the direct modulated square microcavity laser. This may lead to many side modes because of the large optical line. This implies that the number of unwanted modes can be proportional to the loop delay time. To suppress the loop delay we have to reduce the optical fibre length which will lead to reducing the Q factor resulting in low quality of the signal. To overcome this dilemma another architecture for the OEO can be used known as Dual-loop OEO. The dual loop OEO are proposed in our experiment to suppress the undesired side-modes based on the Vernier effect. We shall compare both the single loop and dual loop configuration based on the results obtained.

A. Response at Optical Spectrum Analyser (OSA)

In the experiment described, 14mA of injection current gave tunable microwave signals from 1.8 GHz to 10 GHz with 30 Hz of 3-dB linewidths. At the frequency offset of 10 kHz, the single-sideband phase noises typically were nearly -116 dBc/Hz. The side mode suppression ratio (SMSR) obtained using 14 mA was 32 dB for the first harmonic of the single loop OEO at a wavelength of 1535 nm. The second peak can be observed at 1549 nm. Since we mentioned that the microcavity lasers have fundamental transverse WG mode, the higher transverse modes are seen at the short-wavelength side. Since the wavelength interval depends on the refractive index, for the first-order transverse modes around 1535nm is nearly 1.2 nm. After increasing the injection current at 34 mA, single-mode lasing at the wavelength of 1551.6 nm gives 41 dB SMSR. Also, we can see the redshift of about 2.2 nm after the increase in the injection current to 34 mA from 14 mA which is the result of the thermal effect.

Fig 2b also represents the modulation response under 14 and 34 mA of DC bias currents. A peak height of 7 dB and a resonance frequency of 8.4 GHz can be observed at 14 mA. The modulation bandwidth of 11.4 GHz can be seen, although the

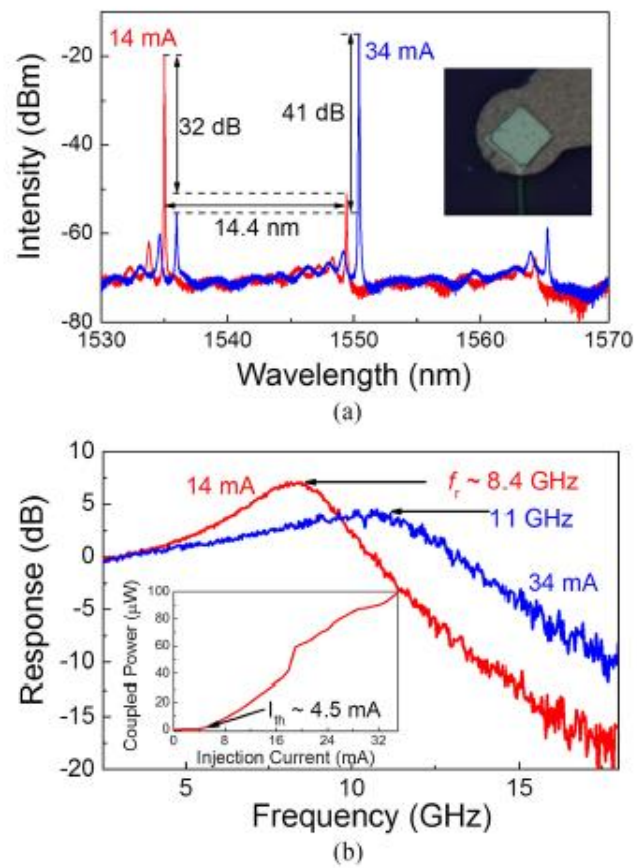

Fig. 5. (a) Lasing spectra of the square microcavity laser at OSA for injection current of 14 mA and 34 mA. Inset in (a): Microscopic image of the square microcavity laser. (b) Small signal response of the microcavity laser. Inset in (b): Single Mode Fiber coupled power versus the injection current.

peak decreases to 4 dB for the resonance. Thus to achieve a high-quality signal the square microcavity laser is DC biased at 14 mA which has a high EO modulation efficiency.

B. Response at Electronic Spectrum Analyser (ESA)

Fig 3a shows the spectrum with the resolution bandwidth (RBW) of 100 kHz in the case of single-loop OEO. The dominant frequency can be observed to be at 4.95 GHz of 5 dBm. Along with the dominant frequency, other harmonics are

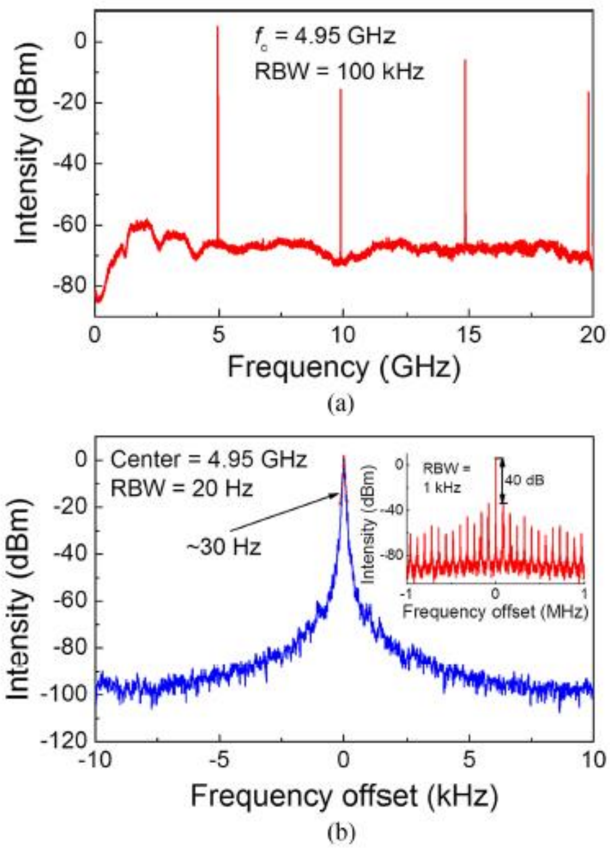

Fig. 6. (a) Microwave spectrum observed at ESA for single-loop OEO. (b) Spectrum centred around 4.95 GHz (RBW= 100 kHz, span= 20 kHz). Inset in (b): Microwave spectrum centred around 4.95 GHz (RBW= 1 kHz, span= 2 MHz)

also observed at 9.8, 14.85 and 19.8 GHz, with -15.6, -5.9 and -16.6 dBm of intensities respectively. The inset in 3b zooms in the first harmonic at 4.95 GHz with an offset of ±1 MHz and 1 kHz of RBW. We can observe multiple sidebands spaced at a frequency of approximately 80 kHz (which can be described as

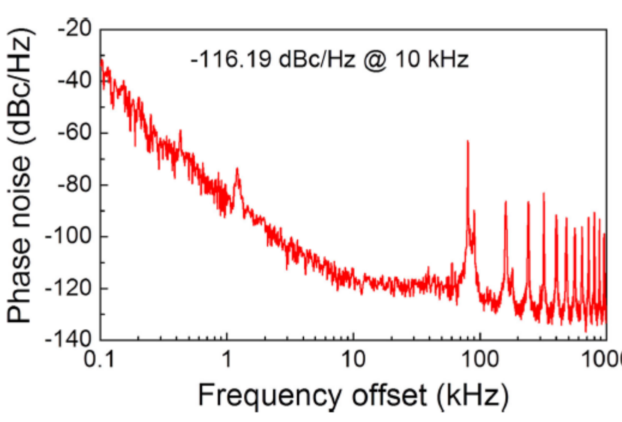

Fig. 7. SSB phase noise spectrum of the first harmonic signal at 4.95 GHz

a free spectrum range (FSR)) due to the long fibre loop and with an SMSR of 40 dB. The FSR is inversely proportional to the length of total delay time, i.e the length of the optical fibre. From 3b the 3-dB linewidth can be observed of 30 Hz with a 0.3 kHz span around the peak. The value of intensity obtained at the 10 kHz frequency offset is -100 dBm approximately which indicates a low phase noise for the generated microwave signal.

To understand the phase noise property we can see the SSB phase noise in fig 4 for the first harmonic frequency at 4.95 GHz for the range of 0.1 to 1000 kHz. The SSB phase noise can be seen of nearly 116.9 dBc/Hz at 10 kHz frequency. The overall noise in the OEO is mainly due to the components in OEO such as a photodetector, electrical amplifier and filter, especially the square microcavity laser-based direct modulator. From the fig. we can also observe additional peaks at an integer multiple of 80 kHz, corresponding to the self-sustained oscillation of side modes. Also, there are minor peaks which are the electrical noises of the feedback loop. We get a maximum frequency of the generated microwave narrow line-width signal at 11 GHz, which is almost equal to the 3-dB modulation bandwidth of direct-modulated microcavity laser. At frequencies out of this range, the EO modulation efficiency degrades since the loss starts dominating the gain in the cavity. The overall SMSR can be concluded not very high due to multiple side modes which are induced in the long fibre loop of Single-loop OEO.

V. Response of the Dual Loop OEO

The SMSR obtained in the case of single-loop OEO was reported and to improve the obtained SMSR, dual-loop OEO was proposed. The fundamental frequency obtained by the dual-loop OEO was not the same as that of the single-loop OEO. However, the feedback signal frequency is tuned from 1.85 GHz to 10.24 GHz. The response at ESA with a resolution

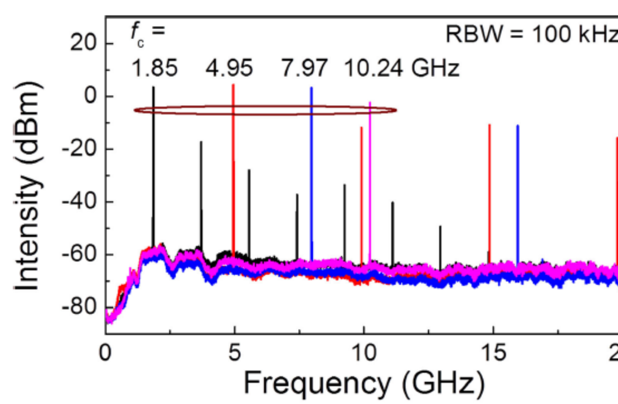

Fig. 8. Optical spectra at OSA for the dual loop OEO with RBW=100 kHz. .

bandwidth of 100 kHz can be observed from fig. 6a in which the feedback frequencies of 1.85, 4.95, 7.97 and 10.24 GHz can be observed. Since we can see that the peaks obtained in the case of dual-loop OEO have lower intensities as compared to 3 to 5 dBm. Thus as compared to the single loop OEO the cutoff frequency and the output power of the electrical signal were relatively low. The possible explanation of this observation was the light splitting and combining process into the dual loop system since it has extra loop loss. The corresponding wavelength interval of 0.014 nm was observed in the OSA at the frequency of 1.85 GHz.

Figure 7a shows the ESA response of the microwave spectrum centred at 4.95 GHz with a resolution bandwidth of 20 Hz and a span of 20 kHz. The linewidth could be measured of 28 Hz which is low relatively low than the single-loop of OSA of 30 Hz but the difference was not found to significant. The SSB phase noise can be observed at 7b at 10 kHz frequency offset as low as -116.04 dBc/Hz. Inset in fig 7a explains the multiple peaks obtained in the dual fibre loops, and also the FSR which can be seen here is not uniform as in the case of single-loop OEO. Since due to the Vernier effect the FSR though have been suppressed but has not ceased to exist. Hence we can see

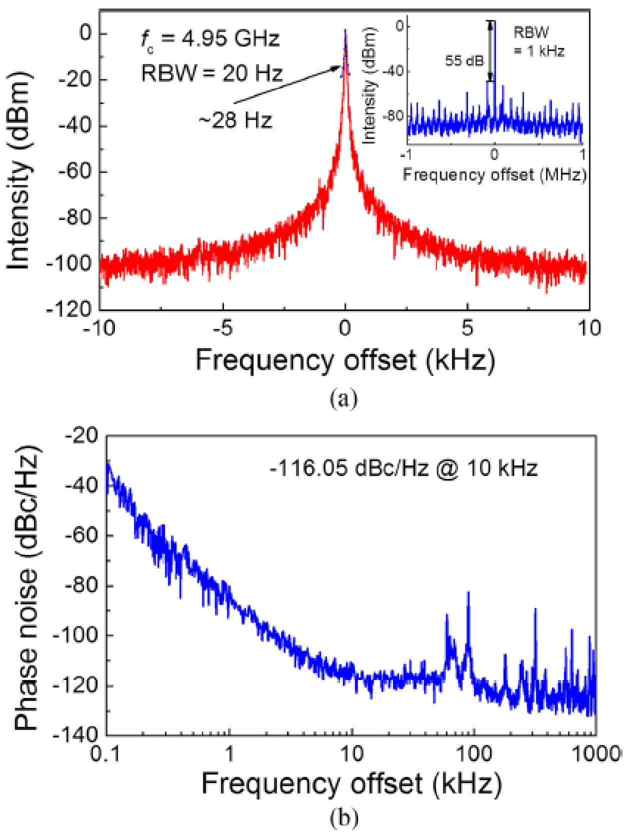

Fig. 9. Microwave spectrum obtained by dual-loop OEO measured by ESA. (a) Microwave spectrum centered around 4.95 GHz (RBW=20 Hz, span= 20 kHz). (b) SSB phase noise of first harmonic signal at 4.95 GHz (RBW=1 kHz, span= 2 MHz)

small peaks in between the 80 kHz which are suppressed in the dual-loop OEO due to the vernier effect. The SMSR obtained, in this case, is nearly 55 dB, which is 15 dB greater than the single loop OEO. Moreover, this architecture can be further optimized for achieving even higher SMSR though the cutoff frequency and the output power of the electrical signal are degraded a little bit. This can be anyway overcome by increasing the loop gain for the extra losses introduced by the dual-loop OEO.

Finally, the SMSR and SSB phase noise at 10 kHz frequency offset is plotted in fig 8 for the dual-loop OEO at a tuning range of 1.85 to 10.24 GHz. The signal quality can be seen to be degrading at 10.24 GHz because of the 3-dB bandwidth of the direct modulated square microcavity laser.

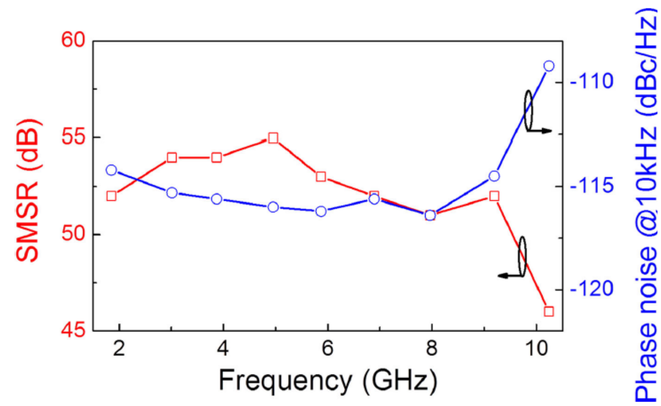

Fig. 10. SSB phase noise and SMSR for first harmonic tuned from 1.85 to 10.25 GHz.

VI. Conclusion

In summary, we have discussed the working of optoelectronic oscillators and the respective blocks and their functions. We looked into the direct modulated AlGaInAs/InP microcavity semiconductor laser and the high quality of microwave signals generated under the injection current of 14 mA without the optical injection. We briefly discussed the Whispering Gallery Modes (WGM) and their significance for producing high Q-factor in the cavity of the OEO. The narrow linewidths were observed in the experiment discussed above with single and dual loop of OEO architectures. In dual-loop OEO we also overviewed the Vernier effect and its impact over FSR in the output microwave spectrum. The SSB phase noises were as low as 116 dBc/Hz in the process which makes the use of OEO a desirable device for the resolution application such as continuous wave Doppler radars. Based on the OEO we can also find a great deal of research over MMIC integration of the OEO and the advantages and disadvantages for the monolithic optoelectronic integrated photonic microwave generation.

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