A Novel Low Phase Noise Push-Push Oscillator Employing Dual-Feedback Sub-Oscillators

Elton Lima[*], Takayuki Tanaka, and Ichihiko Toyoda

Abstract—In this paper, a novel X-band push-push oscillator employing dual-feedback sub-oscillators and a half-wavelength microstrip line resonator is presented. The dual-feedback sub-oscillator consists of a series feedback commonly used in conventional oscillators due to its good phase noise performance and a parallel feedback circuit which improves both the output power and stability. The resonator and power combiner form a single circuit allowing compact size. Measured results show that an excellent output power of +13.3 dBm was obtained at the second harmonic frequency of 9.81 GHz. Moreover, superior phase noise of −105.0 dBc/Hz and −123.5 dBc/Hz were achieved at 100-kHz and 1-MHz offset frequencies, respectively. The suppression of undesired harmonic signals, namely fundamental and third harmonic signals, are 27.9 dB and 55.7 dB, respectively. With a simple design structure and compact size the proposed push-push oscillator achieved very good performance.

1. INTRODUCTION

High performance, low phase noise and low-cost microwave and millimeter-wave sources are essential in modern communication systems. The determining parameters of high-quality microwave and millimeter wave oscillators include low phase noise, high output power, high temperature stability, small size, low cost, high efficiency, and reliability. These factors are essential in driving other circuitries like mixers and PLL synthesizers.

In conventional fundamental oscillators, the generation of highly stable signals at high frequencies is a challenging task because of the lower quality factor of the resonator and the reduced gain of the active device. To circumvent some of these problems, a dual-feedback oscillator topology proposed in [1] aims to enhance the negative resistance and efficiency of the oscillator at high frequency. This configuration was employed in [2] as a method to minimize the phase noise of an oscillator by improving the loaded Q of a planar resonator.

The push-push oscillators have attracted much attention as an effective method to extend the frequency range of active devices and also improve the phase noise characteristics [3–14]. A push-push dielectric resonator oscillator (DRO) using parallel feedback to output high power is illustrated in [7]. Nevertheless, dielectric resonators are difficult to integrate in planar circuits due to their three dimensional structures. To overcome this drawback, planar resonators have been developed and applied to both conventional and push-push oscillators. While most push-push oscillators were designed with a dielectric resonator or resonators with complex structures, the authors in [4] adopted a simplified design approach which uses a microstrip line resonator with 180° phase shift. Although the design configuration is very compact, the phase noise is restricted by the poor Q factor of the resonator. A push-push oscillator using a slot ring resonator is demonstrated in [5] with excellent phase noise, good output power as well as good suppression of the undesired harmonics. However, the design process of the slot ring resonator at high frequency is the major issue. The main focus when it comes to reducing

the phase noise of an oscillator is centered around the design of high-Q resonators [3, 5, 6, 11]. This is because the Q-factor of a resonator strongly determines the phase noise of the oscillator.

In this paper, the focus is on the design of the sub-oscillators instead of the resonator. The sub-oscillators are designed using a series feedback and a parallel feedback technique. The series feedback is commonly used in conventional oscillator to drive the circuit into instability so that it can oscillate. The parallel feedback here is intended to stabilize the resonant mode on the sub-oscillator side, reducing the phase noise. Once the sub-oscillators generate stable signals dynamically, further improvement of the phase noise can be achieved when they are employed in a push-push configuration.

2. OPERATION PRINCIPLE OF A PUSH-PUSH OSCILLATOR

Figure 1 shows a block diagram of a push-push oscillator, which is commonly used to generate the second harmonic signal. It consists of two identical sub-oscillators and a resonator that also acts as a power combiner. The sub-oscillators are coupled through the resonator and oscillate at 180° out-of-phase. This 180° phase difference between the odd signals is produced by the voltage standing wave distribution on the resonator. The signals generated by the two sub-oscillators can be described by Eqs. (1) and (2).

$$V_{\text{out1}} = \sum_n a_n e^{jn\omega_0 t} \tag{1}$$

$$V_{\text{out2}} = \sum_n a_n e^{jn(\omega_0 t + \pi)} \tag{2}$$

where a_n, ω_0 and n are the amplitude, angular frequency and harmonic index, respectively. As all frequency signals have the same amplitude, and the phase difference of the odd signals between the two sub-oscillators is $n\pi$, combining the signals in Eqs. (1) and (2) results in the output signal V_{out} of the second harmonic push-push oscillator as follows:

$$V_{\text{out}} = 2a_2 e^{j2\omega_0 t} + \sum_{n=4,6,8,\ldots} a_n e^{jn\omega_0 t} \tag{3}$$

Equation (3) shows that the fundamental signal and odd harmonics are canceled out, while the even harmonics are constructively combined in-phase at the output network, delivering the second harmonic to the output load.
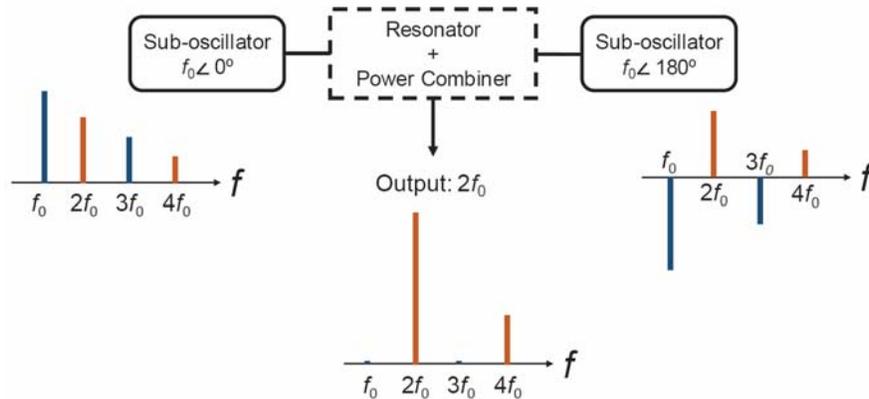
Figure 1. Schematic of a push-push with a resonator that function as power combiner.

Figure 2 shows the proposed push-push oscillator. It consists of two identical sub-oscillators designed employing two feedback types, i.e., the series feedback and parallel feedback. Both sub-oscillators are weakly coupled through a half-wavelength microstrip line resonator. The resonator is also a part of the output network, and the desired signal is extracted at the center of the microstrip line resonator.
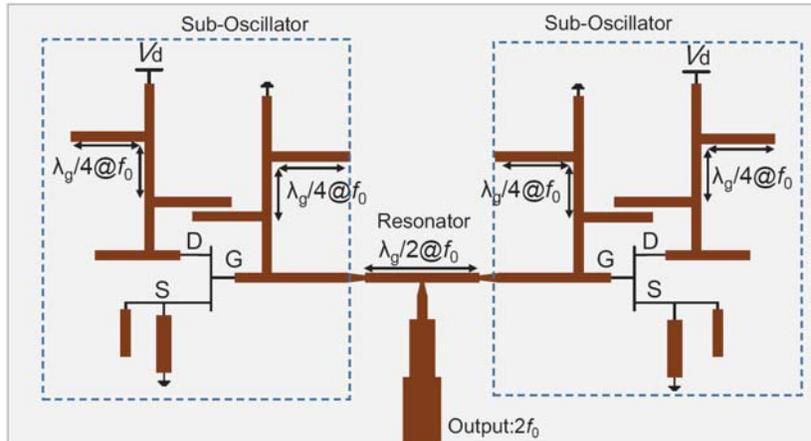
Figure 2. Schematic of the proposed push-push oscillator.

3. PUSH-PUSH OSCILLATOR DESIGN

Figure 3 shows a circuit diagram of the proposed dual-feedback sub-oscillator. An open stub connected at the source of the FET and a transmission line between the source and ground form a series feedback circuit. A parallel feedback circuit is realized by a combination of a phase delay line and edge-coupled lines and works as a voltage transforming element. The edge coupled lines also serve as a DC block, preventing the DC signal to appear at the output port. The parallel-feedback is used to stabilize the sub-oscillator and reduce the phase noise. A part of the sub-oscillator output signal with same fundamental frequency feeds back to the active device, stabilizing the frequency and phase of the sub-oscillator. As stated in [1] this configuration improves the negative resistance and efficiency of the oscillator at high frequency and may result in higher output power. Furthermore, in [9] and [10] a technique known as self-injection shares a similar principle to the proposed design by reusing a part of the generated signal to stabilize the oscillator. The phase delay line on the parallel feedback must be appropriately designed to satisfy both the start-up oscillation condition and low phase noise [2, 9, 10].

The phase delay line in the proposed design can be controlled by changing the coupling space in the parallel feedback path. By increasing the coupling, the reflection coefficient at the port of the sub-oscillator increases, which leads to improvements in the performance of the sub-oscillator. However, the coupling space must be enough to guarantee a proper phase delay that satisfies the start-up oscillation condition. Otherwise, no oscillation will occur in the push-push configuration.

Figure 4 shows a basic structure of the half-wavelength microstrip line resonator with an output
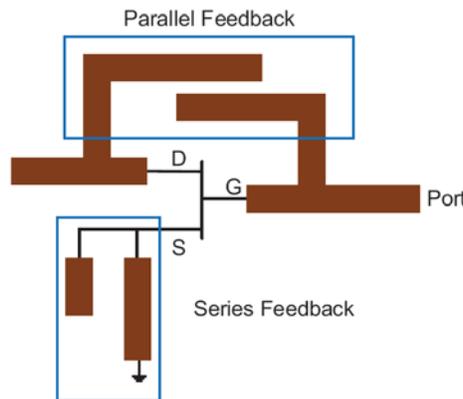
Figure 3. Schematic of the dual-feedback sub-oscillator.
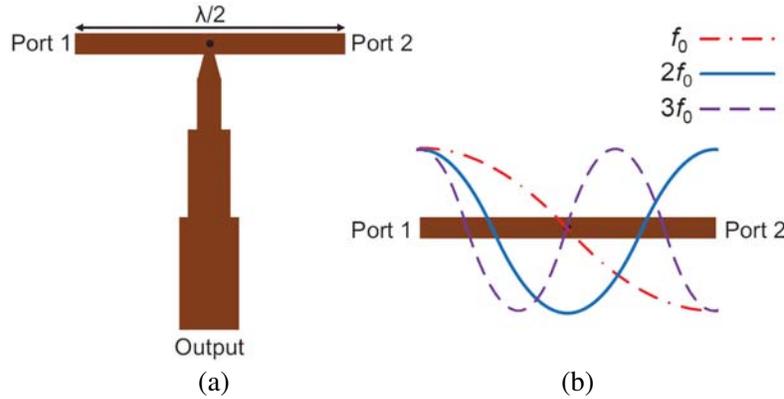
Figure 4. Half-wavelength microstrip line resonator and output network. (a) Circuit diagram. (b) Resonant voltage.

network in a simple T-junction structure and voltage standing waves in the resonator. In Figure 4(a) a symmetric half-wavelength microstrip line resonator functions simultaneously as a common resonator and power combiner. Due to its symmetry, the output signal is obtained from the center of the resonator. This eliminates the need of a Wilkinson power combiner or rat race combiner required in conventional push-push oscillators as in [4], making the circuit size very small. The drawback of the microstrip line resonator is that the Q-factor is not high enough and may impact the phase noise of the oscillator. Figure 4(b) illustrates the resonant standing waves at the fundamental, second and third harmonic frequencies on the microstrip line resonator. Because of the resonant mode of the resonator, the odd frequency signals at ports 1 and 2 are maximum, 180° out-of-phase, and zero at the center of the resonator. Therefore, the desired second harmonic signal is effectively obtained at the output port. The Q-factor generated by the microstrip line resonator is not high enough for an oscillator with excellent phase noise performance. In order to improve the Q-factor, the sub-oscillators are loosely coupled to the microstrip line resonator.
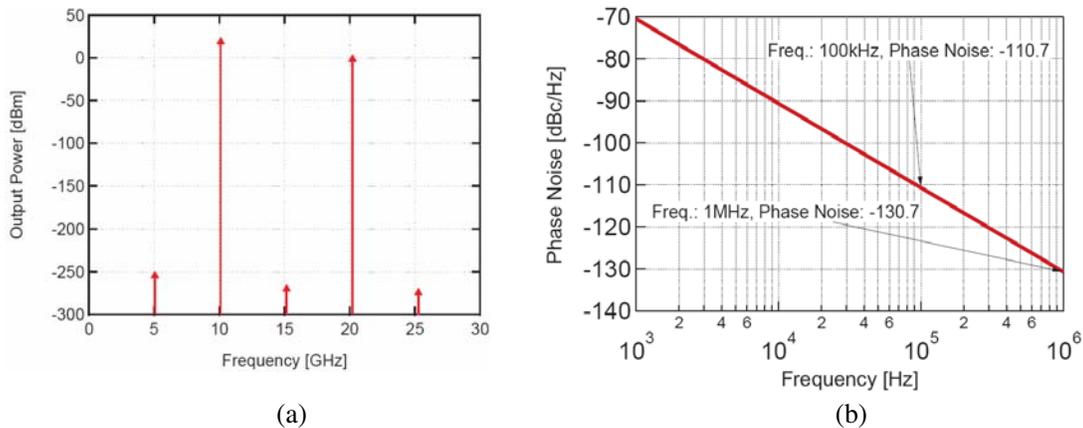
Figure 5. Simulated results for the proposed oscillator. (a) Output spectrum. (b) Phase noise of the 2nd harmonic.

Figure 5 shows the simulated output spectrum and phase noise of the oscillator using Keysight technologies Advanced Design System (ADS). Based on the Harmonic Balance simulation it is observed that the operation of the proposed oscillator confirms the push-push theory as shown in Figure 5(a). As demonstrated by the output spectrum, the second harmonic has the largest power +17.1 dBm followed by the fourth harmonic with +0.037 dBm while the fundamental and odd harmonics are suppressed.

The second harmonic signal has a low phase noise of -110.7 dBc/Hz and -130.7 dBc/Hz at 100-kHz and 1-MHz offset frequencies, respectively, as depicted in Figure 5(b).

4. MEASUREMENT RESULTS

Figure 6 shows a photograph of the fabricated X-band push-push oscillator using dual-feedback sub-oscillators. It is fabricated on a Teflon Glass fiber substrate with a dielectric constant of 2.15 and thickness of 0.8 mm. The circuit is supplied with 0 V gate bias and 4.0 V drain bias. Each sub-oscillator was designed using HEMTs (Avago's ATF34143) to generate negative resistance only at the fundamental frequency of 5.0 GHz. The output power spectrum and phase noise estimation are measured with a spectrum analyzer Agilent E4407B.
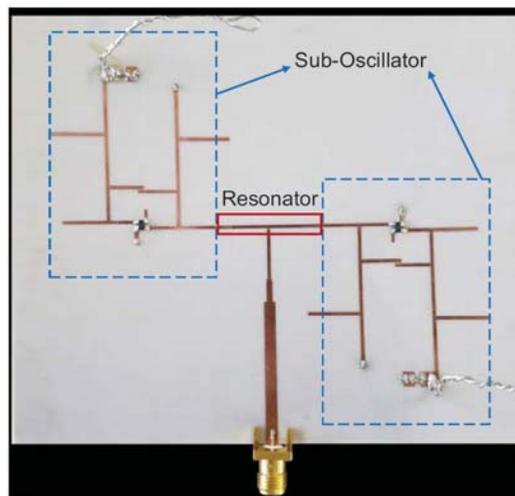
Figure 6. Photograph of the fabricated X-band push-push oscillator using dual-feedback sub-oscillators (112×93 mm^2).

Figure 7 shows the measured power spectrum at the output network of the prototype push-push oscillator. An output power of $+14.4$ dBm at 9.81 GHz was obtained. Furthermore, good suppression of unwanted frequency signals was observed. Because of fabrication errors the frequency of the measured output signal deviated about 300 MHz from the simulated one. Obviously this affected the power of 2nd harmonic and the suppression of the fundamental signal. In order to measure the power of undesired signals, it was necessary to reduce the reference peak of the spectrum analyzer to 5 dBm. The suppressions observed for (f_0), $(3f_0)$ and $(5f_0)$ harmonics are 27.9 dB, 55.7 dB and 55.6 dB, respectively.

Figure 8 shows the phase noise for the maximum bias voltage of 4.0 V. The oscillator exhibits low phase noises of -100.6 dBc/Hz and -121.1 dBc/Hz at 100-kHz and 1-MHz offset frequencies, respectively.

Figure 9 illustrates the effect of the drain bias voltage on the measured output power, power consumption and frequency stability. The second harmonic signal has the highest output power throughout the entire variation of the supply voltage, and good suppression of undesired signals is also observed. In addition, the power consumption increases, and the oscillator becomes less efficient as the bias voltage rises. For a drain bias voltage ranging from 1.2 V to 2.2 V high output power and better efficiency are achieved. The frequencies of both the fundamental and second harmonic signals remain unchanged as shown in Figure 9(b).

Figure 10 shows the measured phase noise as a function of the drain bias voltage. The best phase noise is obtained for a bias voltage of 3.0 V, -105.0 dBc/Hz and -123.5 dBc/Hz. On the other hand, for a bias voltage of 2.0 V the oscillator shows the largest value of phase noise at 100-kHz offset frequency of -99.9 dBc/Hz. However, for this bias voltage a good tradeoff among output power, efficiency and phase noise is achieved.
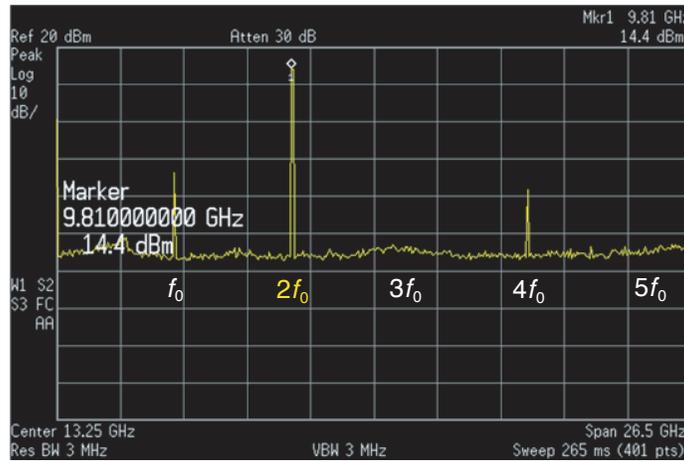
Figure 7. Measured output power spectrum of the oscillator for a bias voltage of 4.0 V.
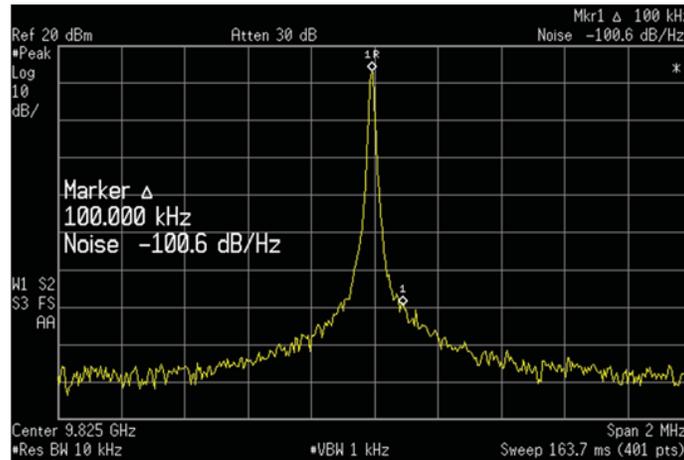
Figure 8. Measured phase noise of the 2nd harmonic for a bias voltage of 4.0 V.
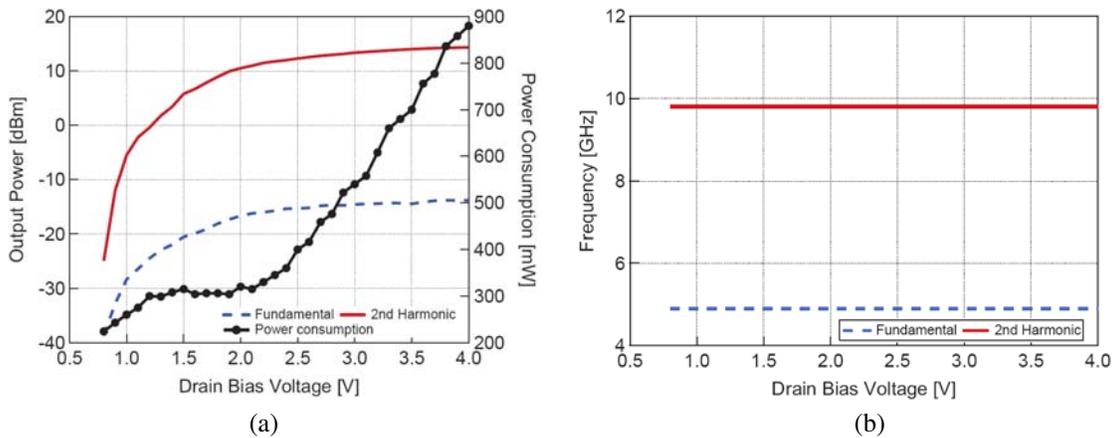
Figure 9. Measured performance with respect to the drain bias voltage. (a) Output power and power consumption. (b) Oscillation frequency.
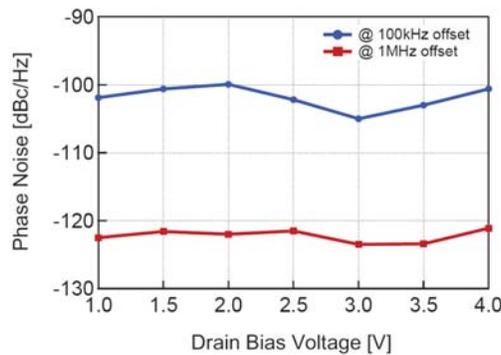
Figure 10. Measured phase noise with respect to the drain bias voltage.

Table 1 compares the performance of this oscillator with previous publications. It is observed that the proposed oscillator displays the best phase noise at 100-kHz offset frequency and the best output power.

Table 1. Performance comparisons between published oscillators and this work.

Ref.	Frequency [GHz]	Output power [dBm]	PN@100 kHz offset [dBc/Hz]	PN@1 MHz offset [dBc/Hz]
[7]	18.9	9.58	−97	- - -
[10]	9.6	−14	- - -	−120.1
[11]	9.883	3.02	−97.67	−127.1
[12]	9.5	7.5	−88	−117
[13]	10–12.28	7	−96	−122
[14]	8.37	−5.4	−101.2	−134.6
This Work	**9.81**	**13.3**	**−105.0**	**−123.5**

5. CONCLUSION

In this paper, a novel low phase noise push-push oscillator using dual-feedback sub-oscillators has been presented. It demonstrates the possibility of achieving low phase noise with a simple microstrip line resonator. This was possible thanks to the dual-feedback sub-oscillators that increase the stability of the resonant mode through the parallel feedback circuit. Accordingly, the stability is analyzed, and the operation principle is verified through a large variation of the drain bias voltage. Moreover, the oscillator yields excellent output power and good suppression of undesired harmonics.

REFERENCES

1. Kwon, Y., D. Pavlidis, T. L. Brock, and D. C. Streit, "A D-band monolithic fundamental oscillator using InP-based HEMT's," *IEEE Trans. Microw. Theory Tech.*, Vol. 41, No. 12, 2336–2344, Dec. 1993.

2. Lee, Y. T., J. Lee, and S. Nam, "A new phase noise reduction method of oscillator by loaded Q improvement using dual feedback topology," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, No. 1, 39–41, Jan. 2005.

3. Pavio, A. M. and M. A. Smith, "A 20–40 GHz push-push dielectric resonator oscillator," *IEEE Trans. Microw. Theory Tech.*, Vol. 33, No. 12, 1346–1349, Dec. 1985.

4. Xiao, H., T. Tanaka, and M. Aikawa, "Push-push oscillator with simplified circuit structure," *Electronics Lett.*, Vol. 38, No. 24, 1545–1547, Nov. 2002.

5. Xiao, H., T. Tanaka, and M. Aikawa, "A low phase noise Ku-band push-push oscillator using slot-line resonator," *2004 IEEE MTT-S Int'l. Microw. Symp. (IMS2004) Dig.*, 1333–1336, Jun. 2004.

6. Choi, J. and C. Seo, "Low phase noise push-push VCO using microstrip square open loop multiple split ring resonator and rat race coupler," *Proc. 2010 Asia-Pacific Microw. Conf. (APMC2010)*, 394–397, Dec. 2010.

7. Du, Y. C., Z. X Tang, B. Zhang, and P. Su, "K-band harmonic dielectric resonator oscillator using parallel feedback structure," *Progress In Electromagnetics Research Letters*, Vol. 34, 83–90, 2012.

8. Su, P., Z. X. Tang, and B. Zhang, "Push-push dielectric resonator oscillator using substrate integrated waveguide power combiner," *Progress In Electromagnetics Research Letters*, Vol. 30, 105–113, 2012.

9. Chang, H. C., "Stability analysis of self-injection-locked oscillators," *IEEE Trans. Microw. Theory Tech.*, Vol. 51, No. 9, 1989–1993, Sep. 2003.

10. Wang, T. P., Z.-M. Tsai, K.-J. Sun, and H. Wang, "Phase-noise reduction of X-band push-push oscillator with second-harmonic self-injection techniques," *IEEE Trans. Microw. Theory Tech.*, Vol. 55, No. 1, 66–77, Jan. 2007.

11. Wu, C. T. M., T. Ithoh, A. K. Poddar, and U. L. Rohde, "Active complementary coupled resonator for low phase noise x-band oscillator," *2014 European Freq. & Time Forum (EFTF2014)*, 356–359, Jun. 2014.

12. He, F. F. and K. Wu, "A low phase-noise VCO using an electronically tunable substrate integrated waveguide resonator," *IEEE Trans. Microw. Theory Tech.*, Vol. 58, No. 10, 3452–3458, Dec. 2010.

13. Florian, C., S. D'Angelo, D. Resca, and F. Scappaviva, "A chip set of low phase noise MMIC VCOs at C, X, and Ku band in InGaP-GaAs HBT technology for satellite telecommunications," *2017 IEEE MTT-S Int'l. Microw. Symp. (IMS2017) Dig.*, 1148–1151, Jun. 2017.

14. Zhang, H., W. Kang, and W. Wu, "Configuration for realizing a push-push parallel-feedback oscillator through a differential bandpass filter," *IEEE Access*, Vol. 6, 28514–28519, May 2018.