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# Design and Performance Evaluation of Ku-Band Positive Feedback Push-Push Oscillator Using Square Split-Ring Bandpass Filter

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**ABSTRACT:** This paper presents a low phase noise positive feedback type Push-Push oscillator employing a balanced bandpass filter (BPF). The BPF consists of an array of split-ring resonators and functions as a frequency selective element in the common feedback loop of the oscillator. Two positive feedback oscillators are coupled to create the 180-degree differential signals required for the implementation of a Push-Push oscillator. The proposed oscillator is analyzed and fabricated. The measured results show that the oscillator works at 15.15 GHz of the second harmonic frequency with an output power of −5.6 dBm. Furthermore, the suppression of fundamental frequency signal is 25.2 dB. Excellent phase noise performance of −100.37 dBc/Hz at 100-kHz offset frequency and −127.13 dBc/Hz at 1-MHz offset frequency is obtained.

## 1. INTRODUCTION

The development of high-frequency oscillators in Ku-band range is crucial for advancing communication systems, radars, and other high-frequency applications. One promising approach to meet this requirement is the use of a Push-Push oscillator. This type of oscillator is often used in a distinct configuration where the fundamental and higher-order odd harmonic signals cancel each other out. However, the second and higher-order even harmonics are built up, resulting in an output that is twice of the fundamental frequency [1]. The Push-Push oscillators have been used for many years to extend the operating frequency of active devices [1–4]. Furthermore, several strategies are adopted to improve oscillator performance, including enhancing the Q-factor of the resonator and group delay of the filter [2–6]. Typically, resonators with high Q factor yield low phase noise oscillators. However, achieving this task on a planar structure is challenging.

In [2], multiple split-ring resonators are utilized to implement a low phase noise voltage-controlled oscillator (VCO). Another study [3] demonstrates that an X-band Push-Push oscillator, employing a parallel feedback configuration with a differential bandpass filter, achieves exceptional phase noise performance of −134.6 dBc/Hz at 1-MHz offset frequency. In [4], an X-band Push-Push oscillator using a balanced BPF in a parallel feedback configuration is proposed. At the oscillation frequency of 9.96 GHz, this design achieves a low phase noise of −128.3 dBc/Hz at 1 MHz offset frequency and power of −8.57 dBm. A low phase noise parallel feedback oscillator based on a substrate integrated waveguide (SIW) dual-mode filtering power divider is presented in [5]. At a frequency of 9.97 GHz, this oscillator achieves a phase noise of −139.6 dBc/Hz at 1-MHz offset frequency. However, SIW resonators are typically larger than planar structures implemented with microstrip technology at the same frequency. A Push-Push oscillator using a dual-feedback sub-oscillator and a quarter-wavelength microstrip-line resonator (ML Resonator) is proposed in [7], achieving a low phase noise of −123 dBc/Hz at 1-MHz offset frequency with an operating frequency of 9.81 GHz. In [8], a positive feedback type Push-Push oscillator is employed within an oscillator array, with injection locking applied to improve stability.

This paper presents a positive feedback-type Push-Push oscillator design aimed at addressing two critical challenges: the generation of high frequency and low phase noise. The proposed balance BPF is constructed as an array of four split-ring resonators and works as a frequency selective device for the fundamental frequency. In comparison to the works presented in [3] and [4], the proposed oscillator features a smaller size thanks to the use of a single bias circuit. Furthermore, the oscillator in [4] incorporates two additional branch-line couplers, leading to an increase in its overall dimensions. The key attributes of the proposed design include:

1. **Compact size**: Utilize fewer components than prior implementations, which represents a key advancement in minimizing size and design complexity.
2. **Frequency accuracy:** The measured results exhibit excellent agreement with the simulated data, underscoring the precise frequency accuracy achieved in the design and validating its potential for practical applications in microwave systems.
3. **Low phase noise:** Low phase noise performance is achieved with reduced design complexity and at much

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higher operating frequency than previous reported designs.

Detailed analysis of the oscillator architecture, feedback network, and harmonic generation mechanism are presented. Experimental results confirm the oscillator's superior phase noise characteristics.

## 2. OSCILLATOR DESIGN

### 2.1. Configuration and Operating Principle

A Push-Push oscillator is a type of oscillator that operates using two identical sub-oscillators in 180° anti-phase operation to generate even harmonics, particularly focusing on the second harmonic, while canceling the fundamental and odd harmonics. This approach efficiently generates high-frequency signals from low-frequency components, offering greater design flexibility and reduced costs. Oscillations are initiated as noise fluctuations in active devices grow in amplitude, ultimately constrained by the gain compression mechanism. In large-signal conditions, the transistor's gain diminishes, matching the total loop losses and establishing a steady-state oscillation with stable amplitude and frequency.

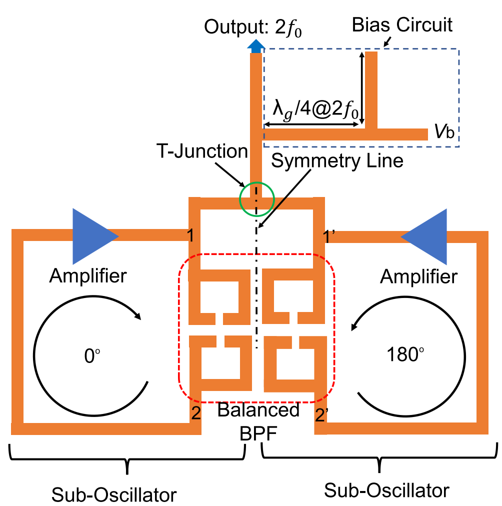


**FIGURE 1.** Proposed Push-Push oscillator using a balanced BPF.

Figure 1 shows the schematic of the proposed positive feedback-type Push-Push oscillator. The structure consists of two identical sub-oscillators, a combiner that form a T-junction, a common bias circuit, and a balanced BPF. The sub-oscillators are coupled to the balanced BPF, resulting in two feedback loops. The feedback network in this parallel setup feeds a portion of the signal back to the active circuit input. Assuming that the sub-oscillators are identical, the output signals of the two sub-oscillators can be expressed as:

$$S_1(t) = \sum_{n=1}^{\infty} a_n e^{jn\omega_0 t} \tag{1}$$

$$S_2(t) = \sum_{n=1}^{\infty} a_n e^{jn\omega_0 (t-\Delta t)} \tag{2}$$

where $a_n$ represents the amplitude information, $\omega_0$ the fundamental angular frequency, and $n\omega_0\Delta t$ the phase difference between harmonic components. Since the two signals are identical in amplitude and frequency but have 180° phase difference, they produce the following output signal.

$$S(t) = \sum_{n=2,4\ldots}^{\infty} 2 \cdot a_n e^{jn\omega_0 t} \tag{3}$$

In this topology, the oscillator can operate in two modes: differential mode (DM) and common mode (CM). When operating in the DM, the fundamental and higher-order odd harmonic signals of the sub-oscillators are 180-degrees out-of-phase with the same amplitude. If the DM is dominant over the CM, it is expected to cancel out the odd harmonics when the signals meet at the T-junction on the symmetry plane. Therefore, a balanced symmetry is critical for canceling the fundamental signal at the output.

On the other hand, high CM suppression is desirable to ensure that only the differential signals are amplified and fed back. This ensures that the Push-Push oscillator operates stably, generating the desired second harmonic signal with low phase noise.

To meet the oscillation criteria, each loop gain must be greater than one, and the phase shift around the loop must be an integer multiple of 360 degrees.

### 2.2. Balanced Bandpass Filter Using Split-Ring Resonator

Figure 2 depicts the balanced bandpass filter. The filter is made up of a four-port network that is arranged into an array of four square split-ring resonators. It is designed to have a center frequency at the fundamental frequency, $f_0$, making it the dominant harmonic frequency in each feedback loop. In this filter, $a$ represents the separation between the sub-filters, $b$ the vertical distance between the split-ring, and $g$ the gap width.

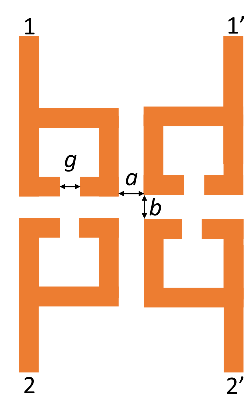


**FIGURE 2.** Basic structure of the proposed balanced BPF.

Since the Push-Push oscillator uses anti-phase operation to cancel out the odd signals and generate the second harmonic, the filter must operate in DM for the fundamental frequency signal. Furthermore, effective CM rejection ensures that only the differential signals are fed back and amplified.

Figure 3 shows the simulated $S$-parameters of the balanced BPF for the gap width, $g$, variation. The center frequency of the

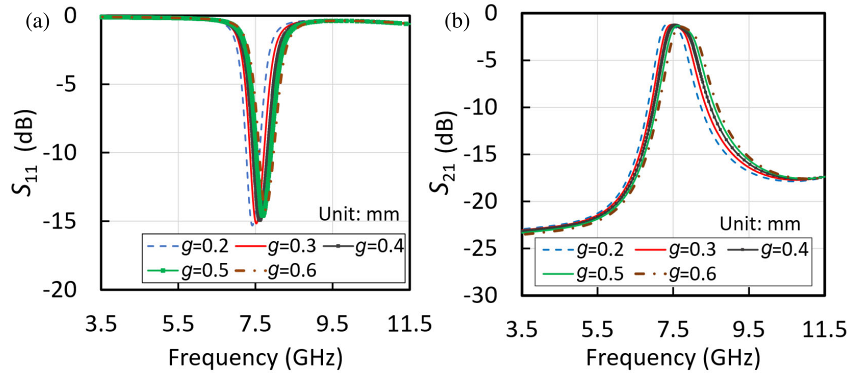


**FIGURE 3**. Simulated $S$-parameters for $a = 1.4$ mm and $b = 0.6$ mm: (a) return loss and (b) insertion loss.

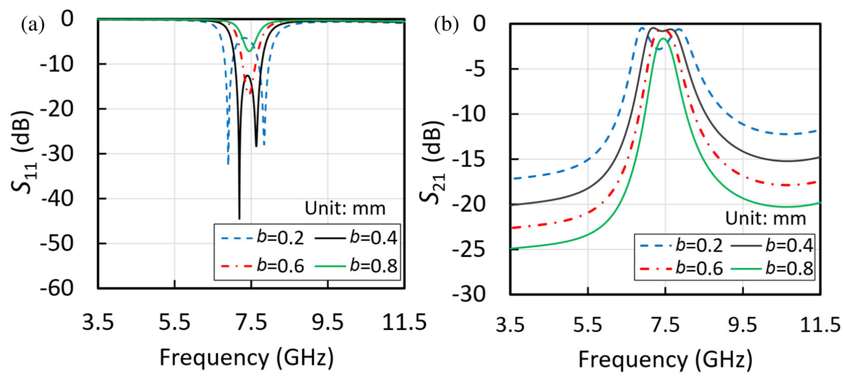


**FIGURE 4**. Simulated $S$-parameters for $a = 1.4$ mm and $g = 0.3$ mm: (a) return loss and (b) insertion loss.

filter is determined by the gap width as shown in Figures 3(a) and 3(b). As the gap width is increased, the center frequency of the filter shifts to a higher frequency, with a frequency variation of 380 MHz. This feature is promising and could be explored to design a voltage-controlled oscillator (VCO).

Figure 4 shows the simulated $S$-parameters for the vertical distance, $b$, between the split-rings. This parameter permits to control the width of the passband of the filter as depicted in Figures 4(a) and (b). When the distance, $b$, is increased, the bandwidth of the filter becomes narrower around the center frequency at 7.5 GHz. This leads to a better $Q$-factor, and consequently better phase noise performance is expected as it can be demonstrated by the following expression:

$$Q_L = \frac{f_0}{\Delta f_{-3\,\mathrm{dB}}} \tag{4}$$

where $\Delta f_{-3\,\mathrm{dB}}$ is the 3-dB bandwidth of $S_{21}$, and $f_0$ is the fundamental resonant frequency. The distance, $a$, does not affect the center frequency nor the bandwidth, but slightly changes the magnitude of $S_{11}$ and $S_{21}$.

Figure 5 shows the structure of the balanced BPF including the output port. The goal is to suppress the CM. In Figure 5(a), ports 1 and 2 are connected by a microstrip line, with port 3 positioned equidistantly between them to maintain perfect symmetry. In contrast, Figure 5(b) incorporates a bias circuit with a $\lambda_g/4$ stub at $2f_0$ in the output. Utilizing a single bias in the output circuit enhances CM rejection without compromising the DM performance. The $\lambda_g/4$ stub at $2f_0$ in the bias circuit is

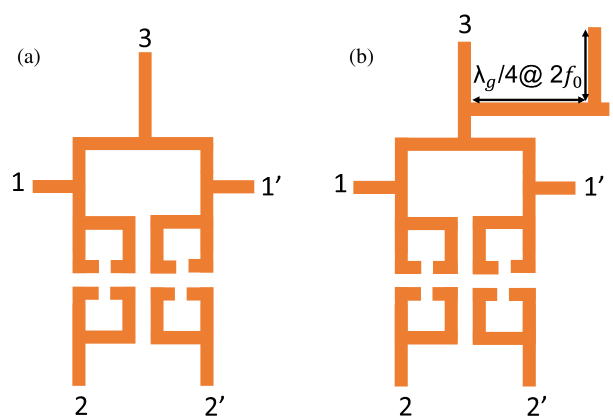


**FIGURE 5**. Structure of the balanced BPF, (a) without bias circuit, (b) with bias circuit.

used to prevent the RF output signal $(2f_0)$ to flow to the DC power supply, while the fundamental signal is suppressed by the circuit.

### 2.3. Design Process and Simulation

The design process of the proposed Push-Push oscillator follows a systematic approach to ensure optimal performance. The process begins with the creation of a balanced BPF that serves as the frequency-selective feedback circuit. This filter, which integrates a combiner and bias circuit, is designed to exhibit appropriate DM passband characteristics and good CM sup-

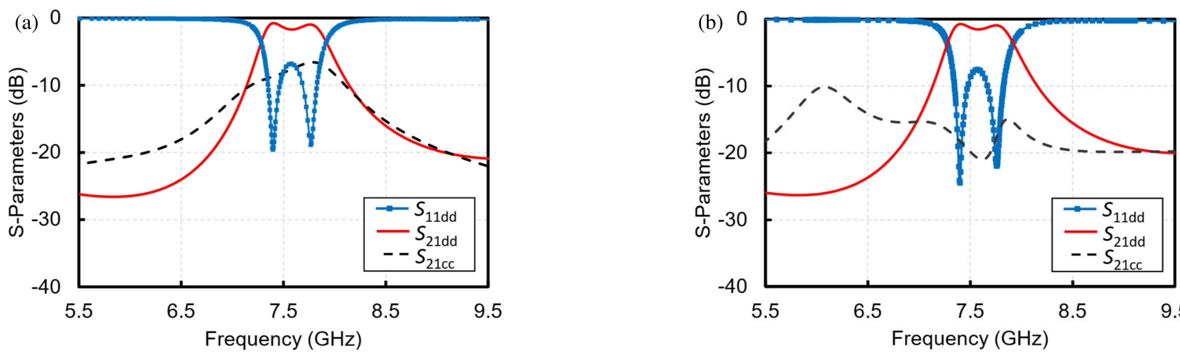


**FIGURE 6.** Differential-mode insertion and return losses, and common mode insertion loss of the balanced BPF, (a) without bias circuit, (b) with bias circuit.

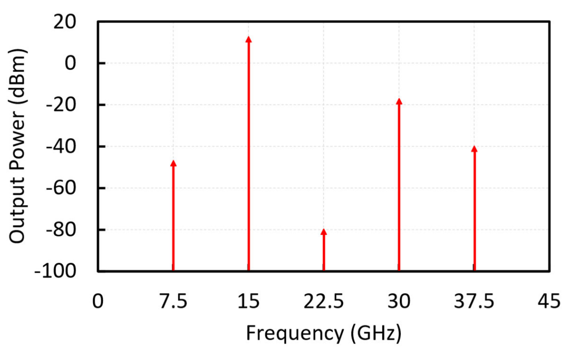


**FIGURE 7.** Simulated output spectrum of the Push-Push oscillator.

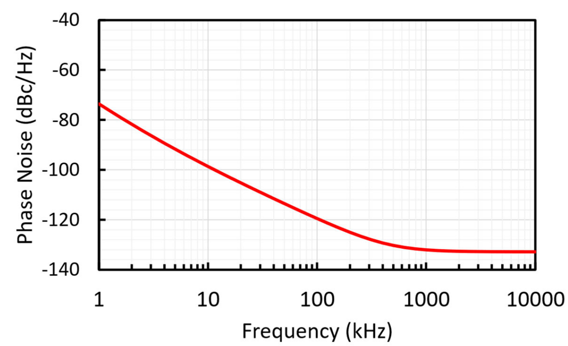


**FIGURE 8.** Simulated phase noise of the Push-Push oscillator at 15 GHz.

pression. Following this, input and output matching circuits for the two amplifiers are designed to provide sufficient loop gain across the operating range of the balanced BPF. Lastly, the lengths of the microstrip lines in each feedback loop are adjusted to meet the required phase condition, ensuring that the total phase shift is a multiple of 360° at the initial oscillation frequency of the Push-Push oscillator. This well-structured approach enables the Push-Push oscillator to achieve superior performance. The circuit is designed using KEYSIGHT Technologies Advanced Design System (ADS) and electromagnetic (EM) simulation tools Momentum.

Figure 6 shows the simulated DM and CM responses of the balanced BPF. In Figure 6(a), the common-mode signal is suppressed across the DM passband. However, while CM rejection is achieved, the maximum suppression level of 6.6 dB may be insufficient to ensure that only the DM signal passes through. This could lead to potential instability in the oscillator. Figure 6(b) shows an improvement in CM rejection when the bias circuit with a quarter wavelength microstrip line at $2f_0$ is incorporated. This level of CM suppression, better than 10 dB around $f_0$, enhances stability in the oscillation.

Figure 7 shows the simulated output power spectrum of the proposed oscillator. As illustrated, the oscillator effectively suppresses the fundamental and higher odd harmonics while enhancing the second harmonic. The simulated output signal is about 11.5 dBm with an operating frequency of 15.01 GHz. The suppressions of the fundamental signal and third harmonic signal are 60 dB and 92.4 dB, respectively.

Figure 8 shows the simulated phase noise of the proposed Push-Push oscillator. At the design frequency of 15.01 GHz, the oscillator achieves low phase noise of $-119$ dBc/Hz at 100-kHz offset frequency and $-131$ dBc/Hz at 1-MHz offset frequency.

## 3. MEASUREMENT RESULTS

Figure 9 shows a photograph of the fabricated prototype. The oscillator is fabricated on a polytetrafluoroethylene (PTFE) substrate with a relative dielectric constant of 2.15 and thickness of 0.8 mm. The transistors used to design the amplifier are

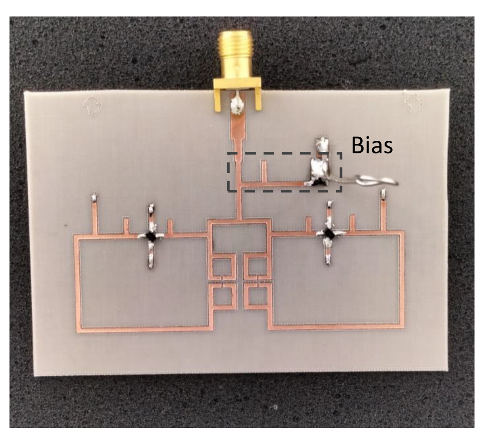


**FIGURE 9.** Photograph of the proposed 15-GHz positive feedback Push-Push oscillator (73 mm × 60 mm).

**TABLE 1.** Physical properties comparison with published Push-Push oscillators.

| Ref. | [3] | [4] | [7] | [9] | [10] | [11] | [12] | [13] | [14] | This work |
|---|---|---|---|---|---|---|---|---|---|---|
| **Substrate** | Rogers 5880 | TLY-5 | Teflon | A25N | Rogers 4350 | TLY-5 | Rogers 5880 | Teflon | Rogers 4350B | PTFE |
| **Dielectric Constant** | 2.2 | 2.2 | 2.15 | — | 3.66 | 2.2 | 2.2 | 2.15 | 3.48 | 2.15 |
| **Resonator** | differential BPF | balanced BPF | ML | SIW | SIW | *SIW/SICL | SIW | Slot-Line | DR | Split-Ring |
| **Device** | HJ-FET | HBT | HEMT | HJ-FET | FET | HEMT | HJ-FET | HEMT | BJT | HEMT |

* SICL (substrate integrated coaxial line)

**TABLE 2.** Performance comparison with published Push-Push oscillators.

| Ref. | $2f_0$ (GHz) | Pout (dBm) | $f_0$ suppression (dBc) | PN (dBc/Hz) 1 MHz | FOM (dBc/Hz) |
|---|---|---|---|---|---|
| [3] | 8.37 | −5.4 | −22.6 | −134.6 | −192.5 |
| [4] | 9.96 | −8.57 | −27.0 | −128.3 | −193.2 |
| [7] | 9.81 | 13.3 | −27.6 | −123.5 | −175.9 |
| [9] | 29.5 | −14.7 | — | −110 | −182.4 |
| [10] | 13.98 | −1.85 | −15.37 | −110 | −170.7 |
| [11] | 25.18 | −6.6 | −13.1 | −120.3 | −192 |
| [12] | 19.76 | 2.9 | −25.28 | −118.1 | −191 |
| [13] | 16.0 | 10.0 | −37.5 | −121.3 | — |
| [14]* | 11.8 | 0.5 | — | −139 | — |
| **This work** | **15.15** | **−5.7** | **−25.3** | **−127.13** | **−182.1** |

* This oscillator employs dielectric resonator (DR).

ATF-34143 HEMTs from AVAGO. The bias circuit incorporates a quarter wavelength stub at $2f_0$ allowing only the second harmonic to pass through. The gate bias voltage is 0 V, and the drain bias voltage is set to 4.5 V, with a total current consumption of 160 mA.

The output spectrum and phase noise of the proposed oscillator was measured using a KEYSIGHT UXA signal analyzer N9040B.

Figure 10 illustrates the measured output power spectrum of the prototype positive feedback Push-Push oscillator. The second harmonic is effectively enhanced, achieving an output power of −5.7 dBm at 15.15 GHz. Furthermore, it demonstrates the effective suppression of undesired harmonics, with the fundamental signal suppressed by approximately 25.3 dB. The power level of the third harmonic is −41.8 dBm, while the fourth harmonic exhibits a power level of −49.4 dBm.

Figure 11 shows the measured phase noise. The oscillator displays excellent phase noise performance of −100.37 dBc/Hz at 100-kHz offset frequency and −127.13 dBc/Hz at 1-MHz offset frequency respectively. Notably, the proposed oscillator exhibits comparable performance to the designs presented in [3] and [4], however, with higher output frequency.

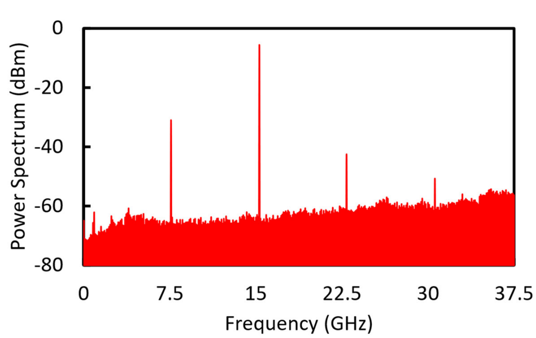


**FIGURE 10.** Measured output spectrum of the proposed Push-Push oscillator.

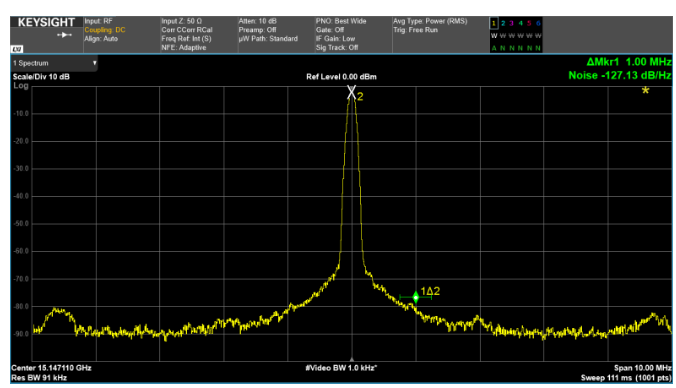


**FIGURE 11.** Measured phase noise performance at 1-MHz offset frequency.

Oscillators operating at lower frequencies generally exhibit superior phase noise performance compared to their high-frequency counterparts. However, achieving low phase noise often requires increased power consumption, highlighting a tradeoff between phase noise and power efficiency. The performance of an oscillator is typically quantified using a figure-of-merit (FOM), which integrates critical parameters such as phase noise, carrier frequency, offset frequency, and power consumption. The FOM is defined as:

$$\mathrm{FOM} = L\left(\Delta f\right) - 20\log\left(\frac{2f_0}{\Delta f}\right) + 10\log\left(\frac{P_{\mathrm{DC}}}{1\,\mathrm{mW}}\right) \quad (5)$$

The FOM of the proposed oscillator is calculated as $-182.1$ dBc/Hz at 1 MHz offset frequency. Table 1 compares its physical properties with published designs. While the oscillators share a similar dielectric constant, they differ in substrate type, resonator, and active device.

Table 2 provides a summary of the performance of this work and compares it with previously published literature on Push-Push oscillators. The proposed Push-Push oscillator demonstrates minimal phase noise while effectively suppressing fundamental frequency components.

## 4. CONCLUSION

In this work, a planar structure is employed to build a low phase noise positive feedback Push-Push oscillator using a balanced BPF. Meanwhile, the filter design incorporating a split-ring resonator array has been examined. Simulations have shown that this oscillator suppresses odd harmonics while enhancing the second harmonic. Experimental results validate the operating principle of the Push-Push oscillator, demonstrating good suppression of the undesired signals. Additionally, low phase noise performance is achieved. With its compact planar design, high performance, and use of a low dielectric constant substrate, this oscillator is perfectly suited for integration into active antenna systems. Its unique combination of features enables compatibility with reconfigurable antenna designs, making it an excellent choice for achieving optimal performance in modern wireless applications.

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