A NOVEL TRIPLE-PUSH OSCILLATOR APPROACH

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ABSTRACT

A novel triple-push oscillator approach is proposed for the first time. This new oscillator topology combines three identical oscillator subcircuits. An analytical formulation is derived to present all the current modes. As will be shown, odd mode currents in each oscillator subcircuit have a 120° phase shift to one another and thus produce in-phase combining for the third harmonic signal. To prove this concept, a 5-GHz triple-push oscillator was designed and fabricated on an FR4 substrate. The measured results showed that at 4.86 GHz, an output signal of 1.7 dBm was delivered with 12.7-dB suppression of the fundamental frequency.

INTRODUCTION

High frequency sources are key components in millimeter-wave (MMW) systems, especially needed for advanced imaging and remote sensing applications. Conventional fundamental oscillators have drawbacks of low Q-factor and insufficient device gain at high frequencies. Recently, push-push oscillators were reported in millimeter-wave frequency range [1]-[4]. Since a push-push oscillator design consists of two fundamental frequency oscillators operating at half the desired output signal frequency, the higher Q-factor resonator and sufficient device gain are easily obtained at half output frequency. Although these advantages are the same with a VCO-doubler topology, push-push oscillators can avoid additional

multiplication, filtering, and amplification required for complete VCO-doubler architecture [1].

In this paper, a triple-push topology is presented for the first time. A triple-push oscillator consists of three identical fundamental oscillators. Both mathematical analysis and time-domain simulation are presented to show that there is a phase shift of 120° among three fundamental signals (f_0). The second harmonic signal ($2f_0$) has a phase shift of 240° , while the third harmonic ($3f_0$) signal has that of 360° . It means that the fundamental (f_0) and the second harmonic ($2f_0$) signals will cancel themselves and the third harmonic signal ($3f_0$), the desired output signal, will combine in phase. Consequently, a triple-push oscillator can extend the usable frequency range and obtain high Q-factor resonator more easily than a push-push oscillator.

In the following sections, a mathematical formulation is derived to present the current modes in a triple-push oscillator. Both simulation results and measured performance of a 5-GHz triple-push oscillator will also be discussed.

ANALYSIS

A mathematical formulation has been reported by R. G. Freitag [5],[6] for mode stability of combined devices. Based on a similar concept, Z-parameters are used to analyze the triple-push oscillator topology. One even mode and two odd modes are obtained and described.

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Fig. 1. (a) The circuit architecture of a triple-push oscillator, (b) the schematic diagram of a subcircuit of the 5-GHz triple-push oscillator.

A triple-push oscillator consists of three identical oscillator subcircuits. Each one includes the active device and matching networks. The circuit architecture defined as a three-port network is shown in Fig. 1(a). The Z-parameter equation of this network is

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}, \quad (1)$$

where Z_{ij} , I_i , V_i are complex phasors for impedance, current, and voltage. Because the three-port network is symmetric, i.e.,

$$Z_{ij} = Z_{ji}, \quad i, j = 1, 2, 3. \quad (2)$$

For the Z matrix in (1), the three eigenvalues and associated eigenvectors are given by

$$\lambda_e = Z_{11} + 2Z_{12},$$

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (\text{even mode}) \quad (3)$$

$$\lambda_o = Z_{11} - Z_{12} \quad (\text{double root}),$$

$$I_1 + I_2 + I_3 = 0 \quad (\text{odd mode}) \quad (4)$$

One even mode and two odd modes exist in a triple-push oscillator. Note that even mode currents are in phase and odd mode currents must satisfy the equation

$$I_1 + I_2 + I_3 = 0. \quad (5)$$

From (5), two independent modes are selected. Assuming that magnitudes of the odd modes currents (I_1 , I_2 and I_3) are equal due to the identity of each subcircuit, each odd mode current must have a 120° phase shift to one another to satisfy (5). This assumption is verified by the time-domain analysis in the next section.

CIRCUIT DESIGN

A 5-GHz triple-push oscillator was fabricated on an FR4 substrate using commercially available PHILIPS BFG540 packaged BJT devices. Device small-signal S-parameters and Gummel-Poon nonlinear models were provided by the manufacturer. Both small-signal and time-domain analyses were performed based on these S-parameters and models. Fig. 1(b) shows the schematic diagram of a single subcircuit with load R_L . A feedback capacitor C_g is used to generate negative resistance, while C_1 and C_2 are used to determine the oscillation frequency. A degeneration resistor R_E is used to make the circuit more stable due to the

temperature variation. C_3 is simply a dc blocking capacitor and L_1 is an RF choke.

The operation principle of a triple-push oscillator is to make the odd modes oscillate but not for the even mode. Small-signal analysis is used to ensure that only odd modes satisfy the oscillation condition but not for the even mode and make an initial prediction of oscillation frequency. In the even mode, even mode currents as well as voltages are in phase at the output node A, which appears as a load R_L with three times of $50\ \Omega$ ($R_L = 150\ \Omega$). In the odd mode, odd mode voltages, which have a 120° phase shift with one another, make output node A behave as a virtual ground ($R_L = 0\ \Omega$). Thus the even and the odd modes are analyzed with a $150\text{-}\Omega$ load and a virtual-ground load respectively.

Time-domain analysis is used to corroborate this design and correctly predict the oscillation frequency. Fig. 2(a) shows three current waveforms (I_1, I_2, I_3) in each subcircuit. Obviously, there is a 120° phase shift among each current waveform, which oscillates at 1.67 GHz (f_0). Fig. 2(b) shows the output signal voltage waveform, which oscillates at 5.01 GHz ($3f_0$). Table 1 lists the simulated results of output power level at the bias point of $V_{CC} = 4\text{ V}$. A 3.4-dBm output power is obtained with 29.0-dB suppression of the fundamental frequency signal and 21.2-dB suppression of the second harmonic signal.

EXPERIMENTAL RESULTS

Figure 3 is the photo of the triple-push oscillator fabricated on an FR4 substrate. Fig. 4 shows the measured spectrum plot of the output signal. A 1.67-dBm output power is delivered to the $50\text{-}\Omega$ load at 4.86 GHz with a phase noise of -95 dBc/Hz at 100 kHz offset. Table 1 lists the measured output power at the bias point of $V_{CC} = 4\text{ V}$ with 90 mA total collector current. As shown in Table 1, good correlations between simulated and measured results are observed. Suppressions of the fundamental and the second

Fig. 2. Time-domain analysis results: (a) current waveforms of I_1 , I_2 , and I_3 , and (b) output voltage waveform.

Fig. 3. Circuit photograph of the 5-GHz triple-push oscillator.

harmonic signals are 12.7 dB and 16.2 dB respectively. Lower output power and suppressions in measurement may be due to variation of active devices and lumped elements as well as the inaccuracy of the model estimation. These discrepancies may result in phase shifts of

fundamental frequency signals in each subcircuit different from 120° , thus the fundamental frequency and the second harmonic signals can not be cancelled completely. Monolithic microwave integrated circuit (MMIC) approaches are preferred to design such triple-push oscillators due to less fabrication variations and tolerance rather than hybrid circuits.

Fig. 4. Spectrum plot of the measured output signal at 4.86 GHz.

Comparison Between Simulated and Measured Results		Frequency (GHz)	Output Power (dBm)
Simulated Results (Time Domain Analysis)	Fundamental	1.67	-25.55
	2nd harmonic	3.34	-17.80
	3rd harmonic	5.01	3.40
Measured Results	Fundamental	1.62	-11.00
	2nd harmonic	3.24	-14.50
	3rd harmonic	4.86	1.67

Table 1. Simulated and measured output power spectrum.

SUMMARY

We have presented a novel triple-push oscillator approach using its third harmonic in-phase combining for the first time. A 5-GHz triple-push oscillator has been implemented to

verify this concept. Based on this approach, frequency sources could be extended to higher frequency range, e.g. millimeter-wave frequency, than that the conventional fundamental and push-push oscillator approaches can provide.

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