

A 2.4 GHz High-Efficiency Low Phase Noise Oscillator Using Combined Band Pass Filter for Harmonic Suppression

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Abstract—This paper examines an efficient low phase noise oscillator using a high Q resonator and harmonic suppression filter. The oscillator is designed using a combined bandpass filter (BPF), which is used as a feedback element to an amplifier. The filter consists of an embedded spur line filter in the L-shaped input and output section which encloses a perturbed square ring. All of these sections are assembled to form a combined BPF which gives an excellent suppression of second and third harmonics. Low phase noise oscillator results are evaluated at 2 V power supply. The measured results show the fundamental frequency at 2.4 GHz, total output power of 14.92 dBm, phase noise -130.92 dBc/Hz at 1 MHz offset frequency, figure of merit (FOM) -175.64 dBc/Hz, reduction in 2nd and 3rd harmonics to below -45 dBm and DC-to-RF efficiency of 51.73%.

1. INTRODUCTION

Radio Frequency/Microwave oscillators are essential components for wireless, radar, and measurement systems. Oscillator key performance parameters like frequency stability, output power, phase noise, DC to RF efficiency, and harmonic suppression must be met in the required systems. The oscillator free-run noise performance outside the loop remains significant and is determined solely by the oscillator and, in particular, by BPF/resonators. The oscillator phase noise is inversely proportional to the quality factor (Q) according to Leeson's phase noise model [1]. Therefore, for better phase-noise, BPFs should have a high Q at resonating frequency. The resonator Q is analytically defined in [2] as

$$Q = \frac{\omega_0}{2} \left. \frac{d\varphi(\omega)}{d\omega} \right|_{\omega_0} = \frac{\omega_0}{2} \tau_d \quad (1)$$

where ω_0 is the fundamental frequency, $\varphi(\omega)$ the resonator phase response, and τ_d the group delay. As reported in [3, 4] maximum unloaded Q resonators were obtained by dielectric resonator and cavity. But due to their size at lower frequencies and fabrication complexity integration with planar structures is challenging. To avoid this fabrication problem planar structure-based resonators from microstrip transmission-line was designed in [5, 6] to be used in planar oscillators. However, the primary issue with planar resonators is that they do not have high unloaded Q and are therefore not suitable for low-phase noise oscillators. For achieving high- Q in planar structures, active filters [7], higher-order BPFs [8], and other techniques [9] were reported. However, active filter had frequency stability, noise, and complex design difficulties, whereas higher-order BPFs occupy large area on the substrate, and their rejection level in stopband also increases. But compared to active filters, higher-order BPF has less design complexity, low noise, and stable frequency. Although higher-order BPFs are designed to select a fundamental frequency, they also pass harmonics. Some harmonics suppression techniques were reported in [10–15]. By using harmonic suppression resonators in the feedback of an amplifier, oscillators

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were designed. To achieve high Q and reduce the effective area, a perturb square structure is introduced in the resonator design. Apart from this structure, spur lines and modified input and output sections help in achieving harmonic suppression.

The block diagram of the proposed low phase noise oscillator is shown in Fig. 1. The Low phase noise oscillator is designed using combined BPF, which is used as a feedback element to a Bipolar Junction Transistor (BJT) amplifier. The combined BPF comprises an embedded spur line filter in the L-shaped input and output section which encloses a perturbed square ring (Dual-Mode BPF). The amplifier is designed using BJT from Infineon BFP 620 with proper biasing lines. The output of the oscillator is taken from the collector side of BJT. Connecting lines are used to assemble Combined BPF and amplifier. The fabricated low noise oscillator measurement shows that it resonates at 2.4 GHz with an output power of 14.92 dBm and phase noise of -130.92 dBc/Hz at 1-MHz offset frequency. The harmonic suppression of -45 dBm is achieved at the second and third harmonics with 51.73% measured DC-to-RF efficiency. Compared to available literature, the proposed low phase noise oscillator has the highest output power and highest DC-to-RF efficiency at 2.4 GHz.

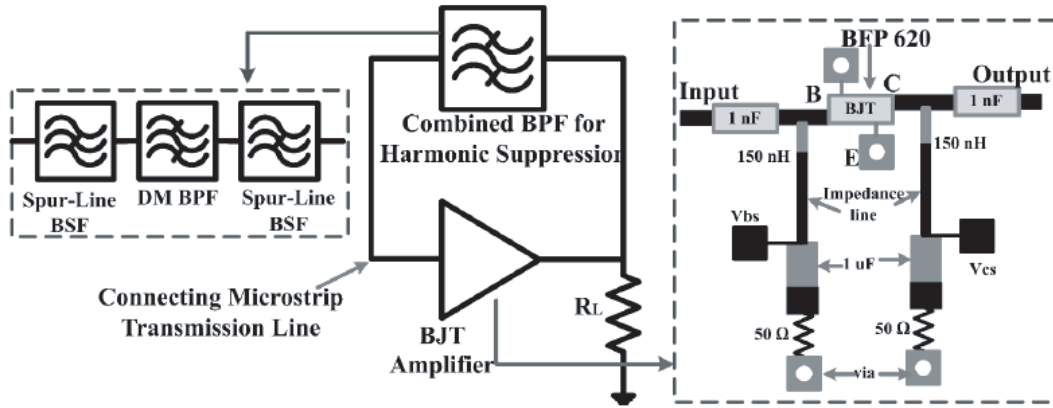


Figure 1. Proposed low phase noise oscillator using combined BPF.

2. COMBINED BAND PASS FILTER

2.1. Second Harmonic Suppression

Conventional square ring resonator (CSRR) reported in [16] was designed with a total length of $l = n\lambda_g$, where n is the no of modes, and λ_g is the guided wavelength. The CSRR shown in Fig. 2(a) is modified according to the application requirements, such as harmonic suppression, quality factor, size reduction, and resonator losses. In CSRR first modification is done at the input and output sections. Instead of using T equivalent transmission line for input and output, the CSRR and L-shaped microstrip lines are coupled by two end-open L-shaped microstrip lines as shown in Fig. 2(b). Harmonic suppression of second-order is accomplished using L-shaped microstrip lines initially suggested in ring-based single-mode BPF (SMBPF) [17]. Fig. 3(a) shows the comparative performance of the CSRR and SMBPF simulated by full-wave simulator Keysight ADS momentum. CSRR result indicates the fundamental frequency at $f_0 = 2.4$ GHz, second harmonic at $2f_0 = 4.8$ GHz, and third harmonic at $3f_0 = 7.2$ GHz whereas SMBPF result shows $f_0 = 2.4$ GHz, $2f_0 = 4.8$ GHz; it decreases below -45 dB, and rejection level is -35 dB up to the 7 GHz. The SMBPF, as shown in Fig. 2(b), can effectively suppress the 2nd harmonics by changing the input and output sections. Also, the stopband rejection is improved by approximately 10 dB, and overall rejection up to 7.0 GHz is 35 dB.

2.2. Quality Factor Improvement

The second modification is made to improve Q . This can be done by higher-order resonators. As the number of resonators increases, the size of overall resonator also increases, resulting in a large size.

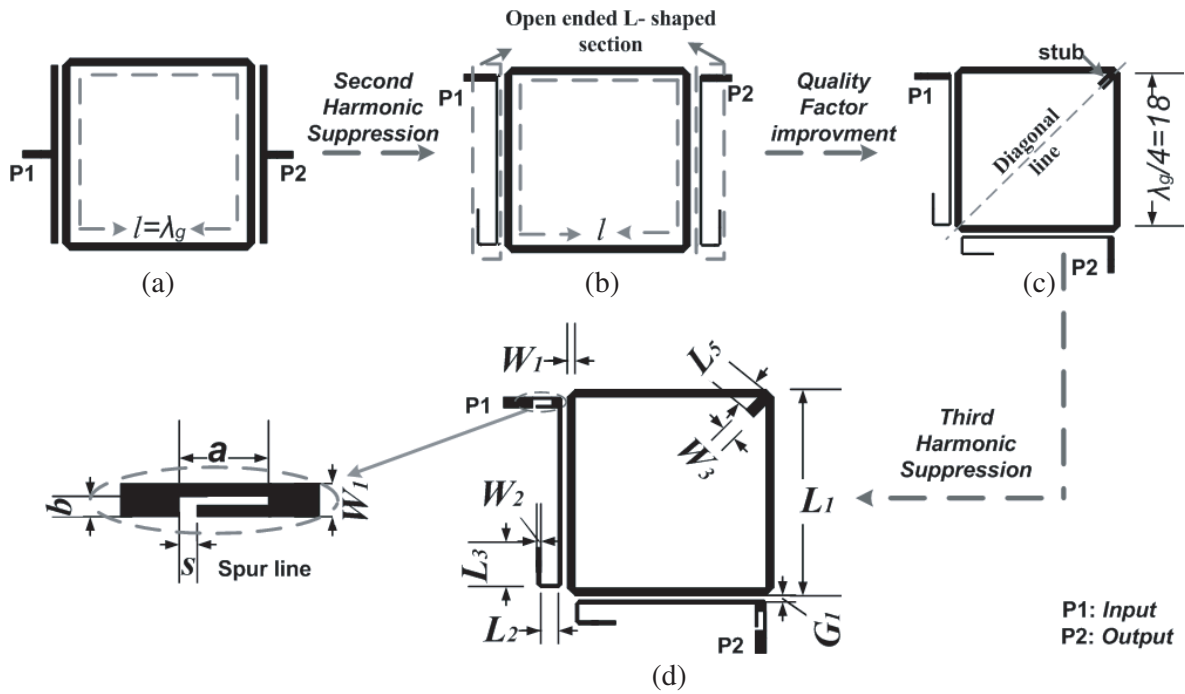


Figure 2. Stepwise formation of combined BPF, (a) conventional square ring resonator, (b) single-mode BPF and (c) dual mode BPF and (d) combined BPF for harmonic suppression.

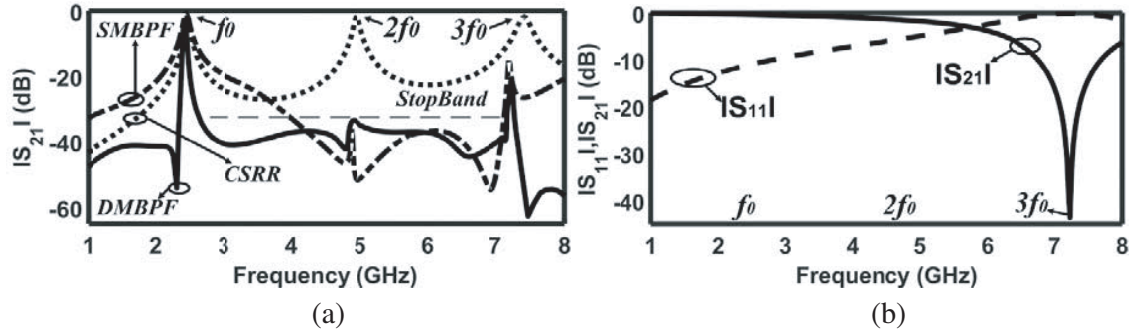


Figure 3. Simulated result of (a) CSRR, SMBPF and DMBPF, (b) spur line BSF.

To reduce the area of the resonator by half and at the same time to achieve high Q , Dual-mode BPF (DMBPF) method was proposed in [18]. In this paper, the symmetry of resonator is perturbed, which acts as a double-tuned resonant circuit. DMBPF reported in [17] is a compact filter in which the number of resonators for a given filter is reduced by half. A stub is connected to the inner corner of the square ring in order to perturb it. Dual-mode resonator input and output sections are arranged symmetrically around the diagonal line as shown in Fig. 2(c). In Fig. 3(a), DMBPF result shows f_0 at 2.429 GHz and keeps the amount of rejection below 31.28 dB up to 7 GHz. Compared to SMBPF results, DMBPF shows higher insertion loss in the passband and lower rejection level in the stopband. This is due to DMBPF performing as a double-tuned resonant circuit. Also, from Fig. 3(a) DMBPF clearly shows sharp passband compared to SMBPF, which is useful in achieving high Q . The simulated quality factor is shown in Fig. 4(b), and the SMBPF and DMBPF have maximum Q of 24.045 and 49 at 2.4 GHz, respectively.

2.3. Third Harmonic Suppression and Spur Line BSF

In DMBPF, rejection level is increased up to 7 GHz, but the third harmonic is around -10.78 dB as shown in Fig. 3(a). There are many methods to remove the harmonics and unwanted higher frequency such as using open-circuit stubs or radial stubs on the square ring or feeding line, stubs etched on backside of the ground plane and by using alternate sections of narrow and wide lines. The DMBPF, whose square ring is sensitive to the symmetry and stubs etched on the backside, is very sensitive to dimensions. For avoiding the issue of integration and convenient fabrication, spurline reported in [19] based on a microstrip transmission line with bandstop (notch) filter (BSF) feature is used. In this paper, spur lines are used to suppress the third-order harmonic ($3f_0$) of DMBPF. Fig. 2(d) shows a schematic of a standard spur line filter. The slot width s , slot length a , and slot height b describe the configuration of the spur line. The slot gap is generally capacitive, while the narrow microstrip line is inductive. The simulated S_{11} and S_{21} are plotted in Fig. 3(b), and it can be inferred from the result that resonance at 7.2 GHz is obtained, effectively suppressing insertion loss by up to -43.65 dB at 7.2 GHz.

2.4. Fabrication of Combined BPF

The combined BPF is designed at 2.4 GHz with harmonic suppression at 4.8 GHz and 7.2 GHz, and its input and output characteristic impedance of the microstrip line is 50 ohms. The combined BPF is fabricated on a 0.508 mm thick Rogers 4350B substrate, with 0.0037 tangent loss and 3.66 dielectric constant. The dimensions of DMBPF are $L_1 = 20.1$, $L_2 = 2.0$, $L_3 = 7.0$, $L_5 = 0.75$, $W_1 = 1.0$, $W_2 = 0.4$, $W_3 = 0.6$ and $G_1 = 0.4$ (in mm). The spur line filter dimensions are $s = 0.4$, $a = 6.5$, and $b = 0.6$ (in mm). Fig. 4(a) demonstrates the outcome of the combined BPF showing fundamental frequency at 2.4 GHz and harmonic suppression at second and third harmonics below 39.52 dB and 41.5 dB, respectively. Also, stopband rejection is below -30.92 dB up to 8 GHz. At fundamental frequency, the measured result agrees well at the fundamental frequency with the simulated results,

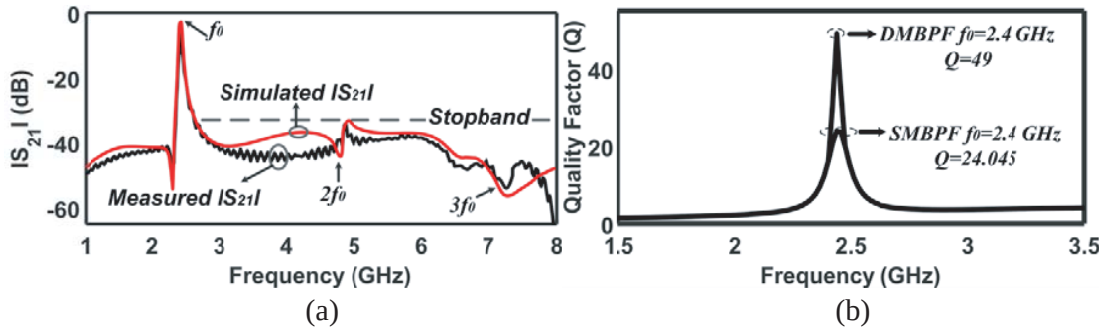


Figure 4. (a) Simulated and measured result of combined BSF, (b) quality factors of SMBPF and DMBPF.

Table 1. Performance comparisons of square ring resonator, spur line BSF and combined BPF.

Filter Topology	f_0^* (GHz)	$2f_0$ (GHz)	$3f_0$ (GHz)	IL** @ f_0 (in dB)	IL @ $2f_0$ (in dB)	IL @ $3f_0$ (in dB)	Rejection level (in dB)
CSRR	2.464	4.958	7.425	1.375	1.599	1.808	-27.05
SMBPF	2.441	4.802	7.208	0.897	46.41	14.71	-35
DMBPF	2.429	4.793	7.243	2.808	42.45	10.78	-31.28
Spur Line	7.2	-	-	43.65	-	-	-
Combined BPF	2.426	4.875	7.247	6.286	39.52	41.5	-30.92

* fundamental frequency, ** Insertion loss

but there is a slight variation at the second and third harmonic frequency suppression. The variation in the dielectric properties of the substrate and fabrication error can be accounted for the difference observed in the simulated and measured results. Table 1 shows the overall performance of CSRR, SMBPF, DMBPF, spur line, and combined filter.

3. REALIZATION OF A LOW NOISE OSCILLATOR USING COMBINED BPF

Two elements are required to design a free-running oscillator: an amplifier and a filter/resonator. Combined BPF is used in feedback for low phase noise oscillator, and for the amplifier, BJT from an Infineon BFP620 is used. Fig. 5(a) shows the layout of low phase noise oscillator. The low phase noise oscillator is designed at 2.4 GHz with the 2nd and 3rd harmonic suppression at 4.8 and 7.2 GHz, respectively. The oscillator components: amplifier, filter, connecting lines, and output line are combined according to “Barkhausen oscillation requirements.” The oscillator loop gain must be slightly higher than unity, and the complete loop phase must satisfy 0° or multiple of 360° .

The layout of the oscillator which has been designed using a combined BPF is fabricated on a Rogers 4350B, as shown in Fig. 5(b). The oscillator produces 2.4 GHz sinusoidal waveform and 14.92 dBm output RF power, as shown in Fig. 5(c). The oscillator is measured using the N9010A Agilent Source Signal Analyzer. The BJT is biased at $V_{cc} = 2$ V with the collector current of $I_c = 30$ mA, and the total power consumed is 60 mW. Fig. 5(d) indicates the measured phase noise -130.92 dBc/Hz at 1 MHz at offset frequency. The oscillator’s figure of merit figure (FOM) [20] is obtained from

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

where $L(\Delta f)$ represents phase noise at Δf offset frequency, f_0 the oscillator fundamental frequency, and P_{DC} the total dc power consumed in mW. Using Equation (2) FOM is calculated as -175.64 dBc/Hz, and DC-to-RF efficiency is 51.73%. Table 2 compares the performance of the proposed work with other

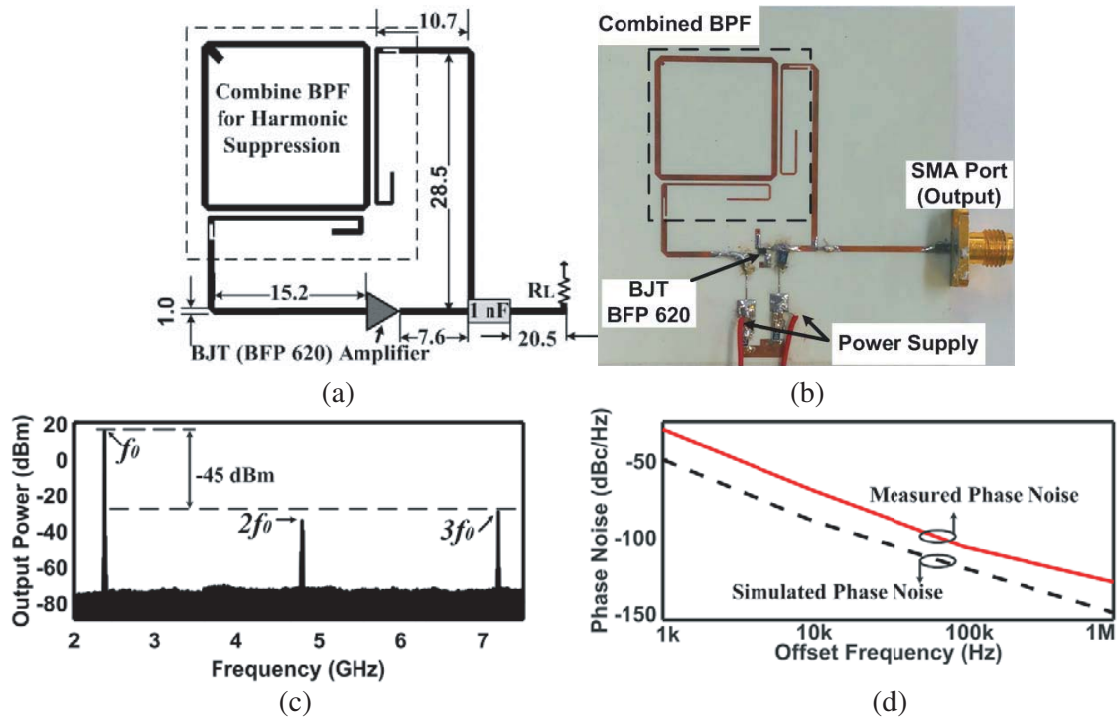


Figure 5. (a) Oscillator layout, (b) fabricated oscillator circuit, (c) measured output power and (d) measured and simulated phase noise.

Table 2. Performance comparisons between reported oscillators with combined filter for harmonic-suppression and this work.

Ref.	Device	Resonator	Frequency (GHz)	Output Power (dBm)	Phase Noise (dBc/Hz) @ 1 MHz	FOM (dBc/Hz) @ 1 MHz	P_{DC} (mw)	DC-to-RF Efficiency (%)
[10]	Si BJT	CRLH	2.05	3.4	-150.4	-207.2	6.1	35.73
[11]	BJT BFP 405	SIR	2.46	3.38	-147.92	-203.18	24	9.04
[12]	BJT BFP 405	Ring Resonator SSB ATL	2.5	0.71	-128.6	-183.6	20	5.88
[5]	BJT BFP 405	Comblane filter	2.28	-2.38	-134.17	-188.32	20	2.85
[13]	BJT BFP 405	TSIR	5.225	-2.7	-132	-193.4	20	2.65
[14]	BJT BFP 405	T-transmission line	2.27	3.94	-129.2	-179.19	20	12.38
This Work	BJT BFP 620	Combined BPF	2.4	14.92	-130.92	-175.64	60	51.73

available filter based oscillators in literature. The table verifies the effectiveness of the proposed low phase noise oscillator.

4. CONCLUSION

In this paper, a low phase noise oscillator is designed and fabricated using a combined BPF and amplifier. The combined BPF acts as a frequency-selective feedback network, and it is realized using dual-mode BPF and spur line BSF. The designed combined BPF demonstrates high Q and excellent 2nd and 3rd harmonic suppression characteristics. The measured phase noise is -130.92 dBc/Hz at 1-MHz offset frequency. The output power and DC-to-RF efficiency of the low phase noise oscillator are 14.92 dBm and 51.73%, respectively, which are much higher than the reported literature. It is possible to make the BPF tunable using varactor diodes or other techniques. There is extensive literature on the mathematical design of such filters, for example [21]. This is a direction which we plan to pursue in future.

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