Progress In Electromagnetics Research C, Vol. 9, 75–88, 2009

A LOW COST RF OSCILLATOR INCORPORATING A FOLDED PARALLEL COUPLED RESONATOR

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Abstract—In this paper, we present a low cost RF oscillator design incorporating a folded parallel coupled resonator. The oscillator is designed on FR4 substrate to achieve low cost. FR4 is a low cost substrate but has a poorly controlled dielectric constant and high loss tangent thereby challenging the design of higher performance circuits. This oscillator operates in 900 MHz band, delivers an output of −3.13 dBm and has phase noise 101.8 dBc/Hz at 10 kHz offset. The size of the folded parallel coupled resonator is 16% smaller than the conventional parallel coupled resonator, thereby making the overall circuit more compact. The power output and phase noise results are better than the oscillator designed with conventional resonator. Open loop analysis method has been adopted for the oscillator design and analysis. The measured data shows good agreement with the simulated results. The performance parameters of this oscillator make it suitable for use in low cost wireless communication solutions in 900 MHz band.

1. INTRODUCTION

The last few decades have witnessed a revolution in the wireless communication. Consequently, there is a need for variety of wireless solutions to replace existing wired systems. Of the three basic wireless

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ranges, applications of short range wireless systems exceed that of long and intermediate systems [1]. Short range applications include wireless security systems, data links, bar code readers, wireless keyboard, and automotive keyless entry, garage door and gate openers electronic personal ID, remote meter sensing, animal tagging, wireless mice and joysticks. The growing influence of these systems on our daily lives has forced system designers to come up with products that deliver higher performance at lower costs. Lower power consumption and reduced size are other design goals being actively pursued because there is a demand to decrease the cost and power consumption by 30% every year [2].

Oscillator is an essential and fundamental system block in every wireless or wired product. The design goals have a significant impact on development of oscillator technology. Apart from the cost, size and power consumption, another important parameter that has been actively investigated in oscillator design is the phase noise. Oscillator phase noise can be effectively reduced by incorporating High-Q resonators [3]. Various types of resonators ranging from planar to 3-D structures have been employed such as quarter wavelength microstrip stub, SAW resonator, coaxial resonator and dielectric resonator [4–7]. While each of the resonator type has its advantages, the planar structures (microstrip based resonators) are a popular and feasible choice in RFIC and MMIC designs because of low cost and ease of integration. However, they suffer from low Q values [8, 9].

Various ideas have been presented to improve the loaded Q-factor of microstrip line resonators [4]. Most of these ideas involve the use of lumped components which adds to the complexity of design. To avoid the use of lumped components and still achieve higher loaded Q-factor, parallel coupled line resonators have been employed in various configurations [7, 9].

Cost of the product is another issue that is related to the intended use of the application and ultimately affects the design of the product. Apart from the component count and technology, substrate choice has a significant impact on the ultimate cost of a product. FR4 is a low cost substrate which has a high loss tangent, thereby, offering challenge for the design of high performance circuits. It is still the most common choice for the design of low cost solutions below microwave frequencies [10].

The primary goal for a microstrip resonator based oscillator design is to achieve low cost and compact size while still maintaining high degree of performance characteristics. This paper presents design of a low cost, low phase noise RF oscillator in 900 MHz band, incorporating a folded tapped coupled line resonator on FR4 substrate.

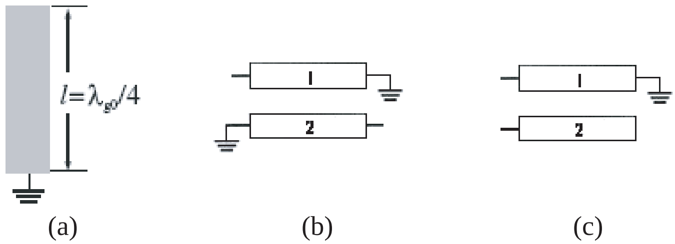


Figure 1. Quarter-wave length microstrip resonator and parallel coupled microstrip resonators.

2. CHOICE OF RESONATOR TOPOLGY

The most commonly employed resonator is the quarter-wavelength resonator in which one end is grounded and the other end is open as shown in Fig. 1(a) [11]. The current is maximum at the grounded end and minimum at the open end while the voltage is minimum at the grounded end and maximum at the open end [12]. This type of resonator allows construction of a compact oscillator but it suffers from low Q value, especially if used on FR4 for low cost solutions. The losses are primarily attributed to dielectric losses which occur near the open end of the resonator. If the resonator length is reduced and resonance is achieved with capacitive loading, then the dielectric losses are reduced and a higher-Q is achieved [12]. The process involves addition of capacitors in parallel to the resonator. This lowers the resonant frequency, which allows the length of the resonator to be reduced to achieve resonance at the desired frequency. Such techniques of capacitively compensating the resonator do result in higher level of performance but at the same time use of lumped components adds to the complexity of design and component count, thereby increasing the production cost.

Parallel coupled resonators, first introduced by Jones and BollJahn [13] had three bandpass structures which could be employed to develop filters and couplers. Two of these basic structures shown in Figs. 1(b) and (c), have been employed in oscillator design to show that they possess higher Q than a single stub microstrip resonator and therefore offer better phase noise performance [7, 9]. The resonator in Fig. 1(b) was chosen as an initial step for preparation of a modified design with tapped input/output. This resonator was used to develop a new breed of filters known as inter-digital filters [14]. Tapped input/output was introduced in place of conventional transformer coupling to reduce loading of resonator and achieve narrower bandwidths [15]. Moreover, closer the tapping point to the grounded end the better is the Q. This dependency can be used to provide low loss resonators.

3. PRELIMINARY DESIGN

An oscillator comprises of a frequency selective network and an amplifier connected in a positive feedback loop as depicted in Fig. 2. The preliminary design of the frequency selective network was based on the tapped interdigital resonator filters [16]. The design of the resonator begins with the selection of the appropriate substrate which in this case was FR4. The substrate dielectric constant and loss tangent is well documented at the frequency range of interest [4]. The resonator was to be designed to resonate at 929 MHz.

The preparation of the preliminary design involved calculation of even (Z_{0e}) and odd (Z_{0o}) mode impedances, tap distance from the short-circuited end Length (L), Width (W) and Spacing (S) of the resonator for a substrate height of 1.5 mm. Based on these calculations, an initial design was prepared in ADS2006A schematic simulator. It was then modeled and analyzed using MoM based EM simulator, Momentum in ADS2006A. Results of preliminary design along with the desired specifications are presented in Table 1.

Table 1. Simulation results for preliminary design.

Parameter	Desired Value	Preliminary Design
Frequency (MHz)	929	897.4
FBW (%)	3–3.7	4.4
Insertion Loss (dB)	< 8.0	9.3
I/O Impedance (Ω)	50	89.5

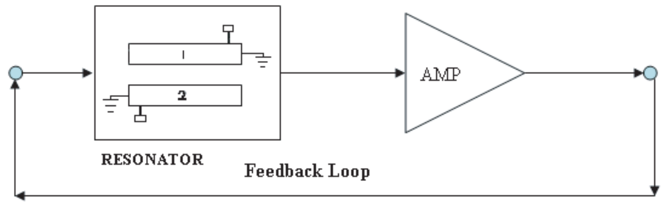


Figure 2. Basic structure of an oscillator circuit.

The comparison in the Table 1 depicts that the results were not according to the desired specifications. The desired performance characteristics can be efficiently achieved with a better understanding of the relationship between variation of physical dimensions of the resonator and its performance parameters. The next section presents details of a sensitivity analysis carried out to develop an understanding of this relationship.

4. SENSITIVITY ANALYSIS

The performance characteristics of the preliminary resonator design show changes when any physical parameter is altered. A detailed study of this behavior provides insightful information on how the variation in any physical attribute affects the resonator performance characteristics. This analysis was carried out by varying one parameter of the preliminary design at a time and then studying its influence on the performance of the resonator.

4.1. Variation in Spacing

The spacing between the coupled resonators primarily affects the bandwidth and insertion loss. As the spacing is reduced, the increase in coupling effect should increase the bandwidth and reduce insertion loss. The spacing between the two parallel resonators was varied between 6–10 mm to study the impact on all the performance parameters. The study shows that insertion loss and bandwidth are strongly dependent on variation of spacing. The insertion loss improves significantly as spacing is reduced. Bandwidth increases as the spacing is reduced. The impact of varying spacing between the resonators on the bandwidth and insertion loss can be studied by observing Fig. 3.

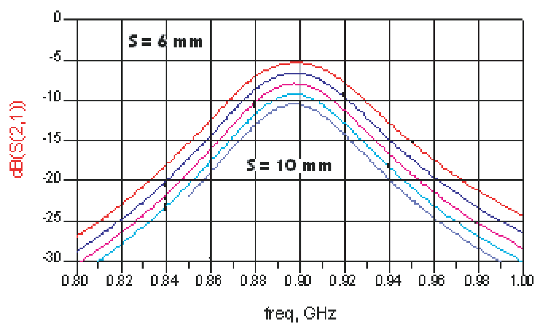


Figure 3. Bandwidth vs insertion loss.

Table 2. Width variation vs performance parameters.

Width (mm)	**Freq (MHz)**	**I.L (dB)**	**BW (MHz)**	**I/O Impedance (Ω)**
3.20	867.7	10.4	37.5	92.78
2.86	897.4	10.5	39.0	94.47
2.60	902.6	10.56	38.6	93.66
2.40	915.4	10.6	39.0	92.64

4.2. Variation in Width

The width of the resonators affects the resistive and conductive losses [11]. The relationship between the conductive losses and width is:

$$\alpha_c = \frac{R_s}{Z_o \times W} \tag{1}$$

where R_s represents the surface resistivity of the conductor and Z_o is the characteristic impedance of the microstrip of width W.

The relationship implies that the width may be increased to reduce the losses. But increasing the width would also entail the placement of tap point very close to the short-circuited end which is not desirable as it causes no problems in computer simulation but will cause inaccuracies in the hardware [7, 17]. The results tabulated in Table 2 depict that frequency is an inverse function of the width and an increase in width lowers the frequency. Other parameters are not significantly affected.

4.3. Variation in Tap Height

The relationship between tap height and fractional bandwidth (FBW) is [16]:

$$\theta_t = \frac{\sin^{-1}\sqrt{\frac{Y \sin^2\theta}{Y_o g_o g_1}}}{1 - \frac{FBW}{2}} \tag{2}$$

where θ_t indicates the tapping position, Y denotes the single microstrip characteristic impedance and g_i represent the element values of a ladder type of lowpass prototype filter.

It can be inferred from Eq. (2) that the desired FBW can be achieved by lowering the tap height. The tap height was varied from 3 mm to 1 mm with a step of 0.5 mm. The study showed that bandwidth and input/output impedance are strong functions of tap height while insertion loss is also significantly affected by variation in tap height.

The results show that as the tap is brought closer to the short-circuited end, the bandwidth reduces and consequently the FBW also decreases. This is in agreement with relationship in Eq. (2). It can be seen from Table 3 that as the tap nears the short-circuited end, the input/output impedance approaches 50 ohms.

4.4. Variation in Length

Resonator length primarily determines the resonant frequency of the resonator. For a given length, the resonant frequency of a quarter-wavelength resonator can be calculated using [18]:

$$f_o = \frac{\lambda}{4} = \frac{c}{4L\sqrt{\varepsilon_e}} \tag{3}$$

where ε_e is the effective dielectric constant.

Equation (3) shows that f_o is inversely proportional to the length of the resonator. As the length of the resonator was reduced, the resonant frequency registered a shift towards the desired frequency.

Table 3. Tap height variation vs performance parameters.

Tap Height (mm)	**Freq (MHz)**	**I.L (dB)**	**BW (MHz)**	**I/O Impedance (Ω)**
3	902.6	10.56	38.6	93.66
2.5	902.1	10.1	34.65	78.05
2.0	901.3	9.82	31.16	63.68
1.5	900.5	9.70	28.18	51
1.0	899.7	9.80	25.71	20.22

Table 4. Length variation vs performance parameters.

Length (mm)	**Freq (MHz)**	**I.L (dB)**	**BW (MHz)**	**I/O Impedance (Ω)**
44.59	900.5	9.7	28.18	51.0
43.59	920.6	9.7	29.33	53.5
43.14	929.9	9.7	29.89	54.7

The variation in length did not have any significant impact on any other parameter as depicted in Table 4.

5. DESIGN OPTIMIZATION

The results of the sensitivity analysis provided an incisive knowledge into the dynamics of the designed resonator. A vivid understanding of the relationship between the physical dimensions of the resonator and their impact on the performance parameters was built. This understanding allowed the optimization of the preliminary design. The analysis carried out had highlighted three parameters that required adjustment namely; resonant frequency, bandwidth and Input/Output impedance.

It was evident from the data compiled that the bandwidth and impedance were strongly dependent on the tap width, whereas, the frequency was dependent on the length of the resonator. The tap height and length were adjusted primarily with only minor variation in spacing and width to achieve the optimized design. The dimensions of the preliminary and optimized design are compared in the Table 5, while a comparison of the desired, preliminary and optimized characteristics is given in Table 6.

6. MODIFIED DESIGN

The characteristics of the optimized design were compared with the desired characteristics and it was observed that the FBW was within

Table 5. Comparison of preliminary and optimized dimensions.

Design	**Length (mm)**	**Tap Height (mm)**	**Width (mm)**	**Spacingv (mm)**
Preliminary	44.59	3	2.86	9
Optimized	43.14	1.5	2.6	10

Table 6. Comparison of performance parameters.

Specification	**Freq (MHz)**	**I.L (dB)**	**FBW (%)**	**I/O Impedance (Ω)**
Desired	929.0	< 8.0	3–3.7	50
Preliminary	897.4	9.3	4.4	89.56
Optimized	929.9	9.7	3.2	54.5

the desired specification. Other parameters like insertion loss and I/O impedance were close to the desired specifications but still needed to be improved. The size of the optimized resonator is 44.8×17.2 mm.

Having developed an understanding of the relationship between the physical parameters and performance parameters, a new design was attempted in which the size of the resonator could be reduced as well as the insertion loss could be improved while maintaining the bandwidth within the desired specifications. This attempt was based on the premise that the increase of coupling increases the mutual capacitance and mutual inductance, which in turn increases the stored energy, thereby, improving the insertion loss as well as the Quality factor [19].

To reduce the size of the optimized design, the resonator was folded inwards from the open circuited ends. The new look of the resonators partially resembles that of a hairpin-line resonator. In a hairpin-line resonator, it is imperative to take into account the reduction of coupled line lengths, while folding the resonator legs. Moreover, if the folded sections of the resonator are closely spaced they function as a pair of coupled lines themselves [11]. The two folded arms of the resonator have respective lengths of 3 and 5 mm. This length is subtracted from the straight line length to make the resonator length 35.14 mm. The impact of this step on the performance characteristics are depicted in Table 7.

Table 7. Performance parameters of folded resonators.

Resonator	**Freq (MHz)**	**I.L (dB)**	**FBW (%)**	**I/O Impedance (Ω)**
Initial Folded	859.9	8.4	3.2	42.6
Preliminary Optimized	929.9	9.7	3.2	54.5

Table 7 shows a decrease in the frequency of the resonator which implies that the length of the resonator can be further reduced so as to achieve the desired frequency of 929 MHz. The insertion loss shows an improvement of 1.3 dB while the I/O impedance decreases below 50 ohms. The knowledge base developed by the sensitivity analysis of the conventional resonator can be effectively utilized to bring the performance parameters of the modified design closer to the desired specifications. A further analysis of length and arm lengths was carried out to bring the performance parameters of the folded resonator within the desired specifications. The two folded arms of the resonator have respective lengths of 3 and 5 mm as depicted in Fig. 4(b). This configuration was chosen after carrying out an analysis on different possible arm lengths. The results of this analysis are presented in

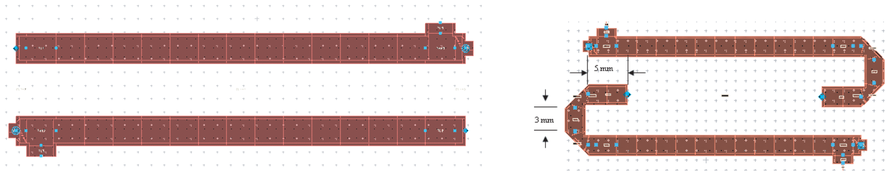
Table 8. The specifications of the finalized design are presented in Table 9 along with a comparison with the preliminary optimized design presented earlier.

Table 8. Arm length variation vs performance parameters.

Length (mm)	**Freq (MHz)**	**I.L (dB)**	**BW (MHz)**	**I/O Impedance (Ω)**
$3 + 5$	929.4	7.36	3.57	46.25
$4 + 4$	930.6	7.89	3.46	48.8
$5 + 3$	932.6	8.33	3.4	50.8

Table 9. Comparison of preliminary and modified resonators.

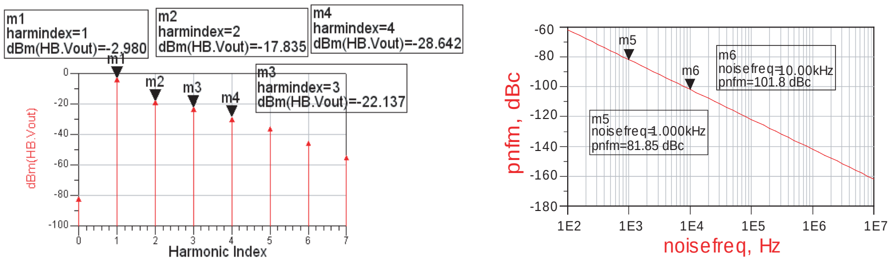
Resonator	**Freq (MHz)**	**I.L (dB)**	**FBW (%)**	**I/O Impedance (ohm)**
Preliminary Optimized	929.9	9.7	3.2	54.5
Folded Optimized	929.4	7.36	3.57	46.25



(a) (b)

Figure 4. Parallel coupled resonators. (a) Preliminary design. (b) Modified design.

The comparison between the conventional and modified design reveals that insertion loss improves by 2.34 dB. Straight line length reduces by 7.20 mm, thereby, reducing the area of the resonator by 16%. Only FBW degrades by 0.37% but it is still within the desired range. Both designs are depicted in Fig. 4.



(a) (b)

Figure 5. Power output vs harmonic index and phase noise.

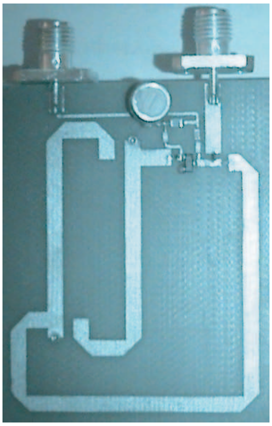


Figure 6. Fabricated oscillator.

7. SIMULATION AND MEASUREMENTS

The oscillator is designed employing the open loop design and analysis procedure [20]. The active device is a BJT AT41533 biased at $I_c = 5\,\text{mA}$ and $V_{ce} = 2.7\,\text{V}$. The output power is tapped from the collector of BJT. ADS2006A was employed to carry out open-loop S-parameter and closed-loop harmonic balance simulations. Fig. 5 shows power in individual harmonic components in dBm. A harmonic index is used to identify the frequency of the component instead of the actual frequency in Hz. As shown Fig. 5(a), the power delivered to the 50 Ω load at the fundamental frequency is −2.98 dBm. The oscillator frequency is 928.1 MHz. The phase noise results are shown in Fig. 5(b). The results show that phase noise levels of −81.85 dBc/Hz and −101.8 dBc/Hz at 1 kHz and 10 kHz offset respectively are achieved.

Table 10. Performance summary of various microstrip resonator based oscillators.

SPECIFICATIONS	[21]	[9]	[19]	[7]	This Work
RESONATOR TYPE	CAPACITIVE LOADED COMBLINE RESONATOR	CAPACITIVE LOADED PARALLEL COUPLED RESONATOR	SQUARE OPEN LOOP	PARALLEL COUPLED	FOLDED PARALLEL COUPLED
FREQUENCY	900 MHz BAND	2 GHz BAND	5.5 GHz BAND	900 MHz	900 MHz
				BAND	BAND
TYPE	VCO	FIXED	FIXED	FIXED	FIXED
VOLTAGE SUPPLY	0–9.7 V dc	3.5 V dc	NOT GIVEN	NOT GIVEN	3.0 V dc
CURRENT SUPPLY	30 mA	8 mA	NOT GIVEN	NOT GIVEN	5 mA
POWER OUTPUT	7 dBm	–3 dBm	–0.5 dBm	3.16 dBm	–3.13 dBm
SSB Phase noise	100 dBc @10kHz offset	110 dBc @1kHz offset	113 dBc @100kHz offset	108.7 dBc @10kHz offset	101.8 dBc @10kHz offset
SUBSTRATE	FR4	NOT GIVEN	TEFLON	RO4003	FR4
% ERROR IN MEASURED FREQ	1.4 %	–	–	2.4 %	1.2 %
SECOND HARMONIC	–28dBm	–22 dBm	–15.33 dBm	–11.32 dBm	–22.84 dBm

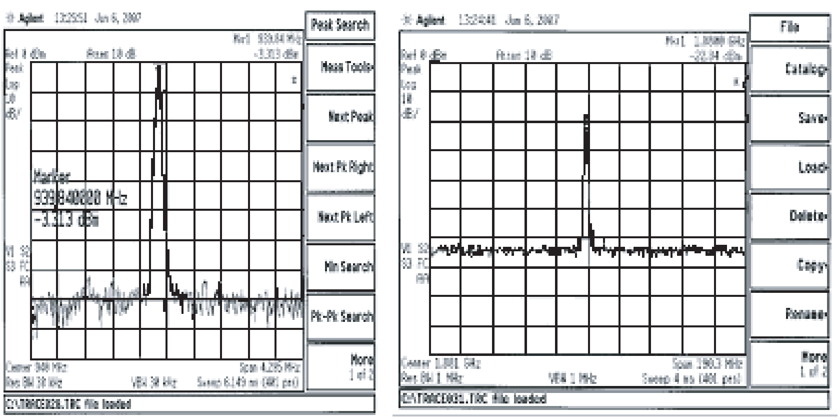


Figure 7. Fundamental frequency and second harmonic.

The oscillator circuit was converted into a Gerber file for PCB manufacturing and a PCB was created on the fabrication machine. The SMD components and connectors were added to the circuit to complete the design for measurements. The fabricated oscillator is depicted in Fig. 6. Oscillator output power, its harmonics and Frequency of operation were observed on the Agilent Spectrum analyzer. The oscillating frequency was determined to be 939.84 MHz as compared to the simulated frequency of 928.1 MHz, an error of 1.2% from the design frequency of 929 MHz. The output power is −3.31 dBm as compared to −2.98 dBm simulated result. The 2nd harmonic is at a level of −22.84 dBm as compared to −17.84 dBm. The results are illustrated in Figs. 7(a) and (b).

Table 10 summarizes the performance of the fabricated oscillator and makes a comparison circuit with the other reported designs. All the works compared here are based on microstrip resonator based oscillators.

8. CONCLUSION

In this paper, a folded parallel coupled microstrip resonator with a higher Q, improved insertion loss and reduced size has been proposed to design an oscillator on FR4, with low production cost. The oscillation frequency and output power of the proposed oscillator are 939.84 MHz and −3.13 dBm respectively. The simulated phase noise results produce an output of −81.85 dBc/Hz @ 1 kHz offset and −101.8 dBc/Hz @ 10 kHz offset. The designed oscillator produces higher power output and better phase noise results than the oscillator designed with the tapped parallel coupled resonator.

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