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Microstrip Square Open Loop Metamaterial Resonator and Rat Race Coupler for Low Phase Noise Push-Push VCO

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Abstract

In this paper, a novel low phase noise voltage-controlled oscillator (VCO) using metamaterial structure and rat race coupler is presented for reducing the phase noise without the reduction of the frequency tuning range. The metamaterial structure has been realized by microstrip square open loop double split ring resonator (SRR). The rat race coupler shows slightly higher transmission compared to a Wilkinson combiner and is, therefore, used instead to improve the performances of VCO. By providing these unique modifications, the proposed push-push VCO has a phase noise of −126.30～−124.83 dBc/Hz at 100 kHz in the tuning range of 5.672～5.800 GHz.

Key words: Metamaterial Sructure, Push-Push VCO, Phase Noise, Microstrip Square Open Loop Double Split Ring Resonator (SRR), Frequency Tuning Range.

Ⅰ. Introduction

The implementation of the low phase noise voltage-controlled oscillator (VCO) has attracted a lot of attention because the phase noise of VCO is one of the most critical elements for the quality of service of the information transfer function. It has been known that he phase noise of VCO depends on the Q factor of the resonator. recently, there has been much interest in high-Q resonators such as split ring resonator (SRR), microstrip square open loop resonator, and hairpin resonator, etc. The high-Q resonator can reduce the phase noise of VCO but has the problem of the frequency tuning range reduction [1], [2].

Metamaterial are composite materials, possess negative permittivity ($\varepsilon < 0$) and negative permeability ($\mu < 0$) simultaneously, proposed by V. Veselago in 1968. Utilizing the idea of Pendry for achieving negative permittivity and negative permeability, this composite material was first fabricated by Smith in 2000 using metallic structures. Push-push VCOs employ two identical sub-VCOs with a balanced operation, causing all odd harmonics to cancel one another out all even harmonics are summed in phase at the output load. Since the design of the resonator in push-push VCOs is performed at half the resonance frequency, a higher Q factor becomes achievable. In addition, push-push VCOs achieve good phase noise performance because it is a type of mutually coupled VCO. Because of these advantages, the push-push principle has emerged as an attractive method for low phase noise VCO design [3], [4].

The low frequency $1/f$ noise plays a dominant role in determining the close to carrier phase noise performance in VCOs. It is well known that $1/f$ noise is up-converted to the carrier frequency, resulting in a $1/f^3$ region at this position. The phase noise of a VCO in the $1/f^3$ region near the carrier frequency depends on the value of the Q factor of the resonator. Because of this, another technique to realize a low phase noise VCO is to employ high Q resonators like dielectric resonators, hair-pin resonators, open loop resonators, split ring resonators (SRRs), and complementary split ring resonators (CSRRs). These resonators have a metamaterial property that results in a higher Q factor. A basic application, then, to increase the coupling coefficient of the resonator is to use double SRRs consisting of concentric split rings in order to increase the distributed capacitance between the strips without increasing the area occupied by the resonator. The square-shaped double SRRs have been also magnetically coupled to the microstrip square open loop structure in order to fabricate efficient stopband structures based on the concept of single negative metamaterial. This structure exhibits high frequency selectivity and is a potential candidate for the design of low phase noise VCO because of its higher Q factor [5], [6].

We have realized the novel VCO that uses a microstrip square open loop double SRR and rat race coupler in this paper.

Ⅱ. Design Principles

Fig. 1 shows the microstrip square open loop double

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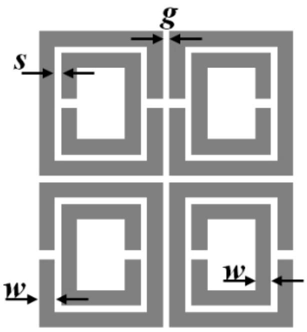
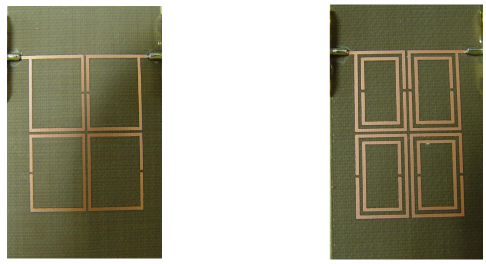


Fig. 1. Microstrip square open loop double SRR.



(a) Microstrip square open loop resonator

(b) Microstrip square open loop double SRR

Fig. 2. Fabrications of each resonator.

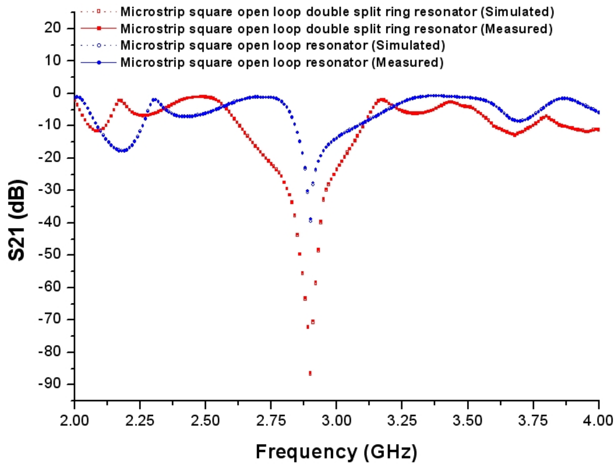


Fig. 3. Simulated and measured results (S_{21}) of a microstrip square open loop resonator and a microstrip square open loop double SRR.

SRR. The square-shaped double SRR represents a straight forward extension of the commonly used circular-shaped SRRs and spiral resonators (SRs). A square-shaped double SRR consists of double concentric square-shaped split rings. The rings are numbered from the outer one to the most inner one, and the distributed capacitances are represented as C_{12}, C_{21}, where the subscript refers to the numbers associated with two rings with which the distributed capacitance is calculated. In the case of distributed capacitances, when the number of the rings increases, a progressive increase of the distributed capacitances is expected. When number of the rings increases above a certain threshold, though, the contribution of the distributed capacitances associated with the inner rings is progressively less significant.

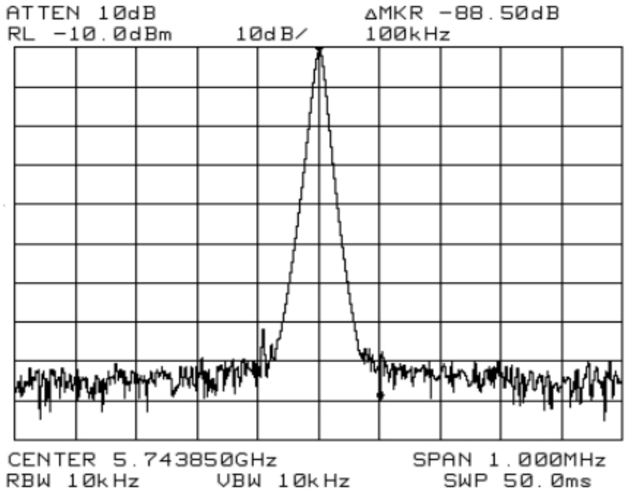
In the case of inductance, a progressive reduction of the inductance is expected when increasing by number. When number of the rings increases above a certain threshold, the reduction of inductance is progressively less significant. When number of the rings increases above a certain threshold, the increasing rate of the total distributed capacitance reduces while the decreasing rate of the total inductance decreases. Therefore, the number of the rings forming the resonator must be selected by considering the resonance frequency and resonator size for removing the unnecessary square-shaped outer rings. The resonance frequency of the double SRR can reduce appreciably up to five rings, while the introduction of further rings may be used to fine tune the resonance frequency.

The square-shaped double SRR also has a larger coupling coefficient, higher rejection, and steeper skirt properties than those of the conventional SRR depending on the increment of the distributed capacitances. This effect yields a higher Q value by the strong coupling. The square-shaped ring has the same linear dimensions but a long strip, leading to a lower resonance frequency compared to one obtained with the circular counterpart. This property makes the square-shaped double SRR ideal both for miniaturization and a higher coupling effect. Its structure has been optimized to obtain high magnetic coupling between the inner and outer rings consisting of each of the open loops as well as high electric and magnetic coupling generated by using the microstrip square open loop structure; as a result, the rejection levels are high in the forbidden bands [5], [6]. In this article, the possibility to improve the phase noise property without the reduction of the frequency tuning range has been demonstrated by using the output matching network based on the proposed harmonic control circuit for the first time.

Ⅲ. Fabrications and Measurement Results

The microstrip square open loop double SRR has been compared with the microstrip square open loop resonator used in our previous work [7] in order to demonstrate the improvement of the performance. In our experiment, the microstrip square open loop double SRR was fabricated on a Taconic TLC substrate with a dielectric constant of 3.2 and a thickness of 31 mils. Fig. 2 shows the fabrications of each resonator. Fig. 3 shows the simulated and measured resonance properties of the microstrip square open loop resonator and microstrip square open loop double SRR. Compared with the simulated results, the measured results are similar to the simulated results obtained by using a High Frequency Structural Simulator (HFSS). As shown in the measured results, the rejection properties of the microstrip square open loop resonator and microstrip square open loop double SRR are −38.9 dB and −81.4 dB at the resonance frequency of 2.8 GHz. It is clear that the microstrip square open loop double SRR has higher rejection and steeper skirt performances than those of the microstrip square open loop resonator at the same resonance frequency. This result is because the couplings of the square-shaped double SRR and microstrip square open loop resonator are constructively added to each other. These couplings result in a very high Q value in the microstrip square open loop double SRR.

The proposed push-push VCO using the microstrip square open loop double SRR and rat race coupler was fabricated on a Taconic TLC substrate with a dielectric constant of 3.2 and a thickness of 31 mils. Each push-push VCO was designed by using NEC's NE661M04 BJT devices and M/A-COM's MA46H202 varactor diodes. Two sub-VCOs are designed to oscillate at half the resonance frequency of 2.8 GHz, and have a symmetrical waveform at the emitter ports by using one common resonator. The phase coupling network is implemented by using the microstrip square open loop multiple SRR with a phase difference of 180°. The correct phase difference between the sub-VCOs is enforced by a properly designed microstrip line. The coupling coefficient value increased by reducing the coupling space between the open loops of the microstrip square open loop structure and the coupling space between the inner and outer rings of the square-shaped double SRR. The increased coupling coefficient value provided the higher Q value, which improved the phase noise performance. The tunable negative resistance designed by connecting the varactor diodes at the negative resistance instead of the resonator, introduced in our previous work [7], has been used for adjusting the oscillation frequency. It is because the frequency tuning range is limited by the high Q property of the microstrip square open loop double SRR. To combine two internal signals, a rat race coupler is designed for operation at $f_{out}=2f_0$ instead of a Wilkinson combiner like we used in our previous work [7]. This type of combiner shows slightly higher transmission compared to a Wilkinson combiner and is, therefore, preferred for our work. Two inputs of a rat race coupler are connected to the emitter ports of two transistors to combine the second harmonics from two sub-VCOs.



(b) Phase noise

Fig. 4. Measured results of a proposed push-push VCO.

The measured results of the output power and phase noise of the proposed push-push VCO are in Fig. 4. The proposed push-push VCO has a phase noise of −126.30 ~ −124.83 dBc/Hz at 100 kHz in the tuning range of 5.672 ~ 5.800 GHz. The output power and harmonics were 9.0 dBm and −22.50 dBc, respectively. The measured output spectrum showed excellent suppression performance of any undesired signals. Considering the RF characteristics of BJTs used in the proposed push-push VCO, the output power of 10.17 dBm indicates that the design of sub-VCOs is suited to generating second harmonics, and the power combining efficiency of the rat race coupler at the desired $2f_0$ signals is remarkably good. Due to the proper design of a loose coupling between the sub-circuits and the microstrip square open loop double SRR, very low phase noise performance is obtained as well. In order to prove the improvement of

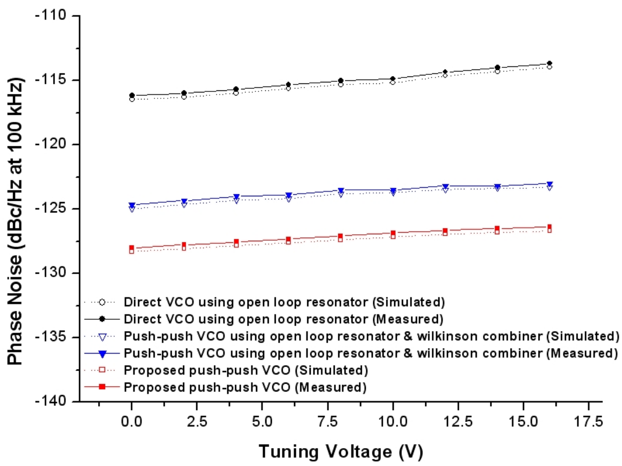


Fig. 5. Simulated and measured results of phase noise properties of each VCO.

the phase noise, the performance of the proposed push-push VCO was compared with the push-push oscillator using the microstrip line resonator [4], the direct VCO using the microstrip square open loop resonator, and the push-push VCO using the microstrip square open loop resonator and Wilkinson combiner [7]. When an offset frequency is 100 kHz, the phase noise properties in these three examples have been −91.00 dBc/Hz, −116.16 dBc/Hz, and −124.67 dBc/Hz at the zero varactor tuning voltage, respectively. The output powers of each VCO have been 2.90 dBm, 4.83 dBm, and 8.67 dBm. Compared with the phase noise performances of these VCOs, the phase noise of the proposed push-push VCO could be reduced to 36.50 dB, 12.74 dB, and 3.95 dB in each scenario. The output power of the proposed push-push VCO also increased to 7.0 dB, 5.12 dB, and 1.20 dB thanks to the use of the push-push structure, microstrip
square open loop double SRR, and rat race coupler. In particular, the increased output power of push-push VCO using a rat race coupler is because the rat race coupler has slightly higher transmission compared to a Wilkinson combiner. Fig. 5 shows the simulated and measured results of the phase noise properties of each VCO. As shown in these results, the phase noise property of the proposed VCO using the rat race coupler has been improved by the increased output power. The measured results are similar to the simulated results obtained by using the Advanced Design System (ADS) simulation tool. The figure-of-merit of the proposed push-push VCO is −206.89∼−204.36 dBc/Hz in the same tuning range.

Ⅳ. Conclusion

We have realized the novel VCO that uses a microstrip square open loop double SRR and rat race coupler. The high-Q resonator has been used for reducing the phase noise. The microstrip square open loop double SRR has a large coupling coefficient value that raises the Q factor value. The rat race coupler shows slightly higher transmission compared to Wilkinson combiner and is, therefore used instead to improve VCO performance. The proposed push-push VCO produces an ideal phase noise of −126.30∼−124.83 dBc/Hz at 100 kHz in the tuning range of 5.672∼5.800 GHz.

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