Design of Low Phase-Noise Voltage-Controlled Oscillator Using Tunable Evanescent-Mode Cavity

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***Abstract*— In this paper, a low phase-noise voltage-controlled oscillator using tunable evanescent-mode cavity is designed, fabricated, and measured. The oscillator is tuned by lumped element varactors placed on the top surface of a substrate-integrated evanescent-mode cavity. The tuning range of the oscillator is 783.6–976.8 MHz with peak output power of 6.97 dBm at 943.2 MHz. Over the tuning frequency the oscillator has a phase noise from -103.8 to -119.4 dBc/Hz at 100 kHz offset frequency and from -141.8 to -152.3 dBc/Hz at 1 MHz offset frequency. The resonator is compatible with RF MEMS tuner to yield a higher resonator Q and better phase noise performance.**

***Index Terms*— Voltage-controlled oscillators, cavity resonator, radiofrequency microelectromechanical systems.**

I. Introduction

Low phase noise oscillator plays a key role in wireless communication system and measurement equipment as local oscillating (LO) signal generator. These oscillators use high quality factor resonators to achieve low phase noise performance and high oscillation stability. The oscillator phase noise is given by [1]:

$$\zeta(f_m) = \frac{FkT}{2P_{avs}}\left[\frac{1}{f_m^3}\frac{f_0^2}{4Q_L^2} + \frac{1}{f_m^2}\frac{f_0^2}{4Q_L^2} + \frac{f_0}{f_m} + 1\right] \quad (1)$$

where F is the noise factor, k is the Boltzmann constant, T is the temperature, Q_L is the resonator loaded Q factor, f_m is the frequency offset, and f_0 is the oscillation frequency. The phase noise of the frequencies near the carrier is proportional to $1/Q_L^2$. Thus, to obtain a good phase-noise performance, the overall quality factor of the oscillator network should be as high as possible. Increasing the quality factor of the resonator will boost the quality factor of the oscillator network. The main types of resonators are YIG resonators, dielectric resonators, distributed transmission line resonators, and surface acoustic wave resonators [2]. YIG resonators have a Q of several thousands and wide tuning range, but it has high power consumption, high fabrication cost, and poor thermal stability. Distributed transmission line resonators have wide tuning range, but has a lower Q around few hundreds. Dielectric resonator and surface acoustic wave resonators both have Q of tens of thousands, but have very limited tuning range [2].

Recently, tunable evanescent-mode resonator (EVA) was demonstrated to achieve wide tuning range while maintaining a high quality factor [3]. The tuning can be achieved by both MEMS tuner and solid state tuner [4]. This paper demonstrates to build a wide-band tunable oscillator using substrate integrated tunable EVA resonators with lumped tuning elements.

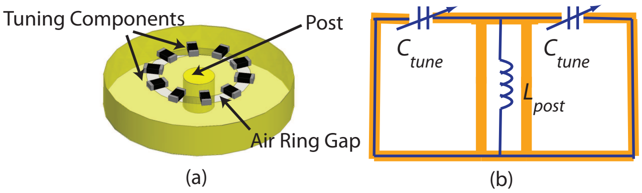

Fig. 1. Schematic of resonator design: (a) PCB with generalized varactor as tuning elements; (b) equivalent circuit model for the proposed air ring gap cavity [4].

II. Oscillator Design

A. Tunable Resonator Design

The resonator design and equivalent circuit model are shown in Fig. 1. A metallic post is placed in the center of the cavity and connects to a pad on the top wall of the cavity, which is separated from the rest of the cavity ceiling by an air gap. Lumped-element varactors are placed across the air gap using standard surface mount (SMT) technology. By changing the capacitance C_{tune}, the resonant frequency of the cavity and the phase shift are changed. This resonator design provides several benefits such as flexibility in choosing tuner, easiness in assembly and commercial availability of the tuner and the substrates [4].

ANSYS HFSS is used to simulate the tunning range and the quality factor across the tuning frequencies. The Q_u of the resonator depends on the Q of the tuning component and the Q of the cavity. For low-Q tuning component, such as solid-state varactor, the Q_u is primarily limited by the Q of the varactor. If high Q RF-MEMS varactors are used, the Q_u of the resonator can be increased.

In this design, the resonator is fabricated on Rogers TMM3 substrate with a thickness of 5 mm and relative permittivity of 3.27. There are two ring gaps. Each ring gap has 16 Skyworks Solution's SMV 1405-040LF diode varactors, with 32 varactors for the resonator. The cavity dimensions were optimized using ANSYS HFSS: 12 mm cavity radius and 0.4 mm post radius. Fig. 2 shows the simulation and measurement results of the tunable resonator. The discrepancy between the simulated and measured quality factor is due to fabrication errors.

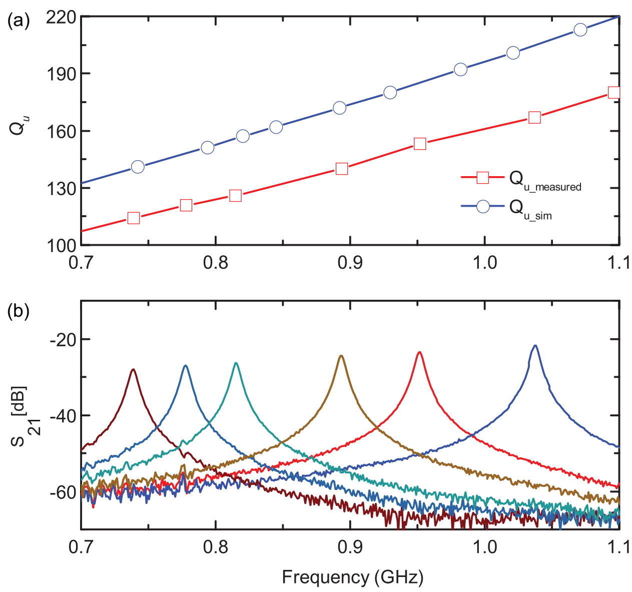

Fig. 2. (a) Simulated and measured Q_u over tuning frequency and (b) measured S_{21} of the resonator.

B. Tunable Oscillator Design and Measurement

The oscillator is designed based on two port negative-resistance oscillator topology shown in Fig. 3. The active

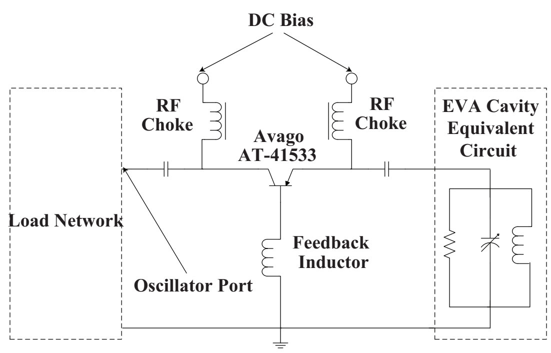

Fig. 3. Two port negative-resistance oscillator circuit topology.

circuit is designed and fabricated on Rogers TMM6 laminates with a relative permittivity of 6.0 and thickness of 1.524 mm. The transistor, Avago AT-41533, is biased at 5.8 V (V_{ce}) with a collector current I_c of 5 mA. The transistor is biased at a lower collector current in order to have a lower noise figure, trading off transistor gain. An inductor is placed at the base node of the transistor to provide feedback and enhance the gain at desired tuning frequencies. Agilent Advanced Design Systems (ADS) is used to calculate and show the amplifier gain peaks of the active circuit under different feedback inductances, which is shown in Fig. 4.

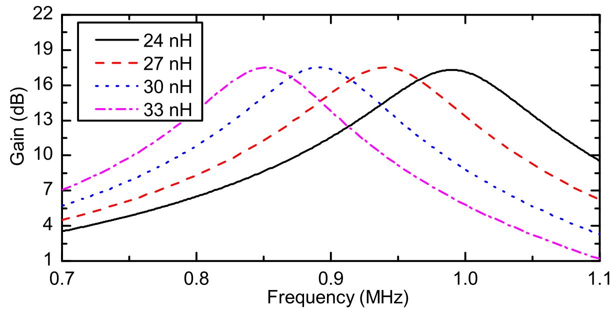

Fig. 4. Amplifier power gain under different feedback inductance.

The coupling between the active circuit and the resonator is realized by making opening at the back of the EVA resonator and the active circuit board. A microstrip transmission line from the active circuit is used as the feed-in to the resonator. The loop gain of the oscillator should be greater than unity before oscillating. The amplifier then saturates and the loop gain becomes unity when oscillating. The oscillation frequency is determined by the frequency when loop phase shift is $0°$ or multiple of $360°$. The length of the feed-in transmission line is selected to provide the correct phase shift at the desired oscillation frequency, which is 6.25 mm long. The oscillation frequency is tuned by changing the phase shift in EVA resonator, which is determined by the capacitance of the varactors. The resonator board and the active circuit board are screwed together to build the oscillator. The resonator board and the active circuit share a common ground plane. The schematic of the oscillator is shown in Fig. 5.

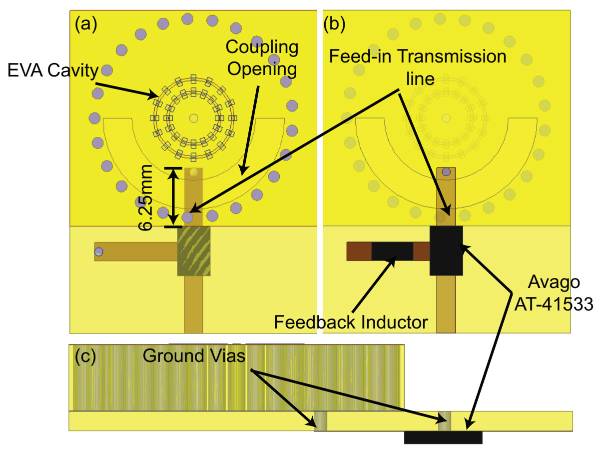

Fig. 5. Schematics of the proposed oscillator (Bias line is not shown) (a) front-view (b) back-view and (c) side-view.

The fabricated oscillator is shown in Fig. 6. Agilent

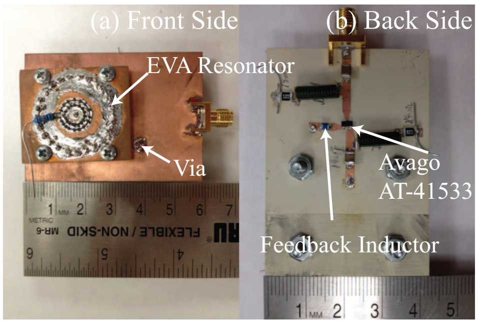

Fig. 6. (a) Front side of the oscillator and (b) back side of the oscillator.

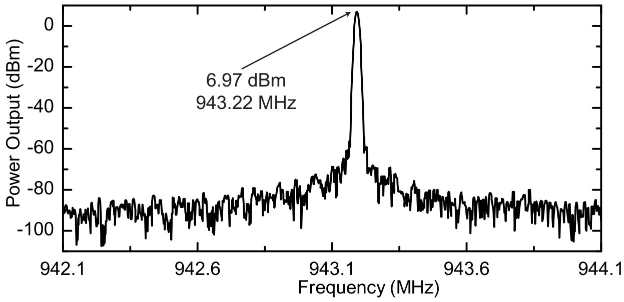

Fig. 7. Spectrum of oscillator output at bias voltage of 18 V.

N9030A PXA Signal Analyzer is used for the oscillator output measurement with a setting of a 10-kHz resolution bandwidth and 2-MHz frequency span. Fig. 7 shows the spectrum at a bias voltage of 18 V. The figure of merit (FOM) can be calculated by [5]:

$$FOM = \zeta(f_m) - 20log(\frac{f_0}{f_m}) + 10log(\frac{P_{DC}}{1\ \text{mW}}) \quad (2)$$

where $\zeta(f_m)$ is the phase-noise at the offset frequency, f_m is the offset frequency, f_0 is the oscillation frequency, and P_{DC} is the DC power consumption in mW. The FOM at 18 V bias is -192.7 dBc/Hz. The tuning range, as shown in Fig. 8, is 783.6–976.8 MHz with highest power output of 6.97 dBm at 943.2 MHz and lowest power output of 0.62 dBm at 783.6 MHz. The output power is measured before any amplification. The phase noise, as shown in Fig. 9, is measured by using the improved phase noise measurement procedure in Agilent N9030A PXA Signal Analyzer, which subtracts the signal analyzer noise [6]. Over the tuning frequency the oscillator has a phase noise from -103.8 to -119.4 dBc/Hz at 100 kHz offset frequency and from -141.8 to -152.3 dBc/Hz at 1 MHz offset frequency.

III. Conclusion

In this paper, a tunable low phase-noise microwave oscillator is developed. The design procedure can be summarized as: 1) Design the active circuit to have a proper

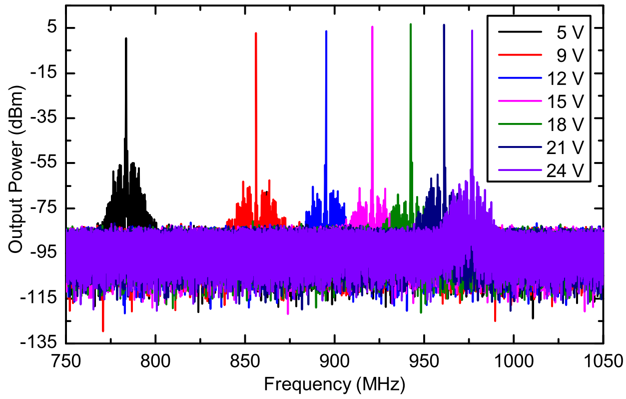

Fig. 8. Measured oscillator tuning range

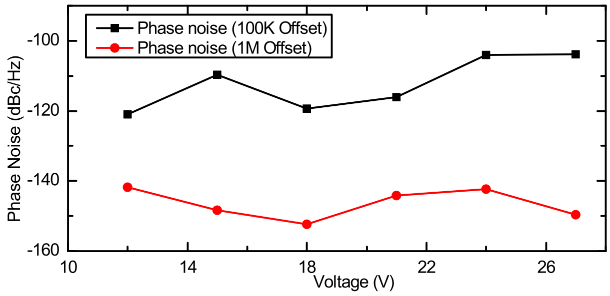

Fig. 9. Phase noise measurement over the tuning voltage

gain at the desired frequency, 2) Design the EVA resonator that can be tuned over the desired frequency. 3) Assembly the active circuit and EVA resonator to built the oscillator. The performance of the oscillator can be further improved by replacing the solid state varactor to RF MEMS varactor or replacing the air-gap EVA resonator to high Q silicon-membrane EVA resonator, while maintaining the same oscillator configuration.

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