Low Phase-Noise Integrated Voltage Controlled Oscillator Design Using LTCC Technology

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***Abstract*—This paper describes the design and implementation of a highly integrated voltage controlled oscillator (VCO) module based upon Low-Temperature Co-fired Ceramic (LTCC) packaging technology. The circuit is realized by embedding the strip-line resonator and lumped passives inside a multilayer LTCC substrate. Measurement results of a silicon bipolar VCO circuit operating at 2.4 GHz is shown. The constructed module is compact in size and has good phase noise performance.**

***Index Terms*—Low-Temperature Co-fired Ceramic (LTCC), phase noise, strip-line resonator, voltage controlled oscillator (VCO).**

I. Introduction

In MODERN RF transceiver design, the close-to-carrier noise performance of the local oscillator is a major consideration due to the small frequency spacing between communication channels. It is also well known that low phase noise performance may be achieved by using high Q resonator. In compared to lumped LC tank circuit, distributed elements like transmission line can offer higher Q factor at the expense of large substrate area. Recently, the use of Low-Temperature Co-fired Ceramic (LTCC) technology [1]–[3] in RF circuit design has become very popular due to its low loss, high integration density, and high reliability. LTCC is a multilayer ceramic technology, which provides an ability to embed passive components in layers while the active elements are mounted on the surface layer. In this work, advanced packaging technology (LTCC) is employed for size reduction by embedding as many passive components as possible inside the multilayer substrate. For illustration, a 2.4 GHz LTCC voltage controlled oscillator (VCO) module using silicon bipolar technology is constructed and characterized.

II. VCO Module Design and Implementation

Fig. 1 shows the schematic diagram of the VCO circuit by utilizing a Agilent HBFP0450 silicon bipolar transistor ($f_{\mathrm{T}} = 25$ GHz at $V_{\mathrm{CE}} = 2$ V and $\mathrm{I_C} = 10$ mA) as the active device. Frequency tuning is achieved by using a Siemens BB833 varactor diode as part of the feedback network. Moreover, a fifth-order lumped-element low-pass filter is inserted at the collector output for the suppression of the harmonic signal. For

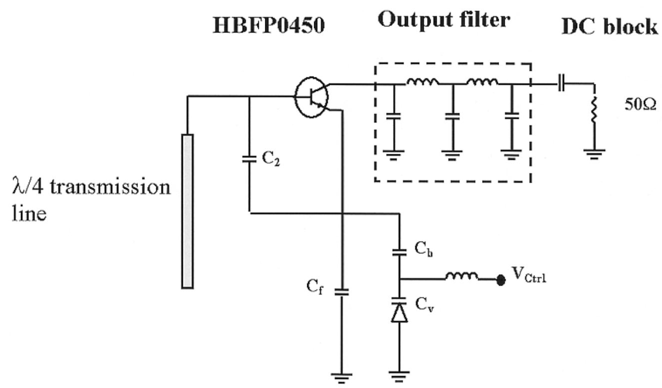

Fig. 1. Schematic diagram of VCO module (Biasing circuit not shown).

size reduction, the resonator, the filter and the feedback capacitors (C_2, C_{f} and C_{b}) are all placed inside the LTCC substrate. Only the transistor, the tuning diode and the biasing circuitry are physically mounted on the upper surface of the substrate. Figs. 2 and 3 show the layout of the $\lambda/4$ strip-line resonator [4] and the layer construction of the LTCC substrate. To avoid radiation loss, a laminated structure is adopted since it has been reported elsewhere [5] that this configuration does not radiate electromagnetic energy if the spacing between via-holes is smaller than a quarter-wavelength. In the design, the vertical sidewall via-holes are equally spaced with a separation distance of approximately 0.02 of a wavelength. Furthermore, a meander-line pattern is chosen for the layout of the resonator due to size constraint.

All embedded capacitors are either parallel-plate or multilayer type, while the embedded inductors are spiral-shaped design. The LTCC substrate is made from DuPont 951AT tape ($\mathrm{loss\ tangent} = 0.005$), with dielectric constant of 7.8 and thickness of 3.6 mil per layer (15 layers in total). Design procedures are basically divided into three stages. First, linear circuit analysis is applied for setting up the oscillation condition at the desired operating frequency range. Then, the layout of individual component (resonator, output filter, feedback capacitors) is designed based on the data provided by the LTCC foundry. Here, full-wave EM solver is employed for fine-tuning the designs. After that, a multiport electromagnetic simulation of all embedded components together with the interconnection are conducted to take into account the coupling and parasitic effect. Performance verification of the complete VCO module is accomplished by integrating the simulated multiport s-parameters of the embedded passives and the device models (surface-mounted components) into the final circuit simulation. Some parameter tuning is required in this step for the adjustment of the

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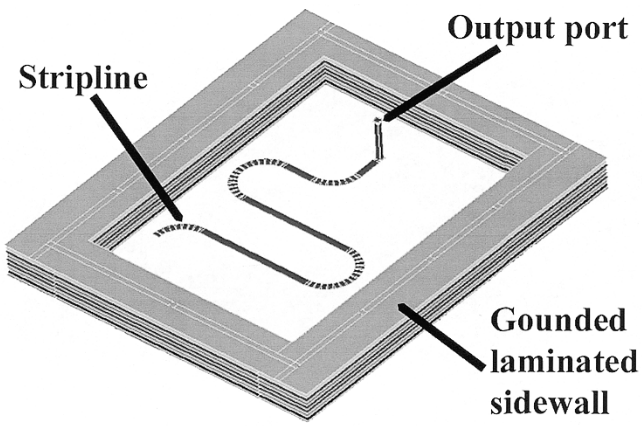

Fig. 2. Meander-shaped laminated stripline resonator.

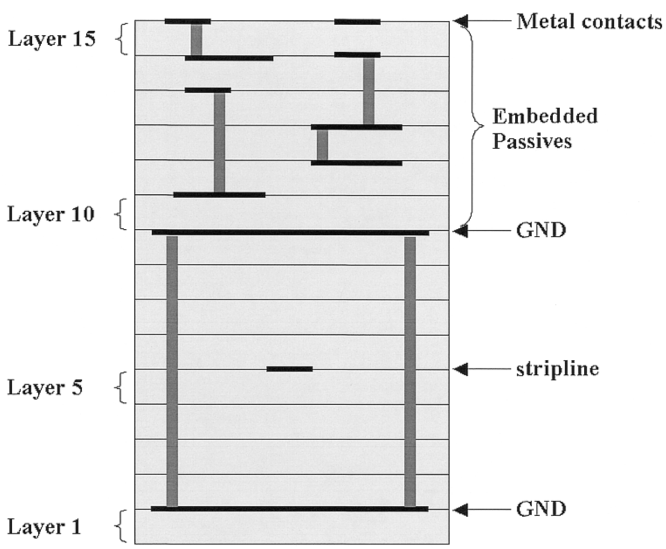

Fig. 3. Cross-sectional view of the LTCC substrate.

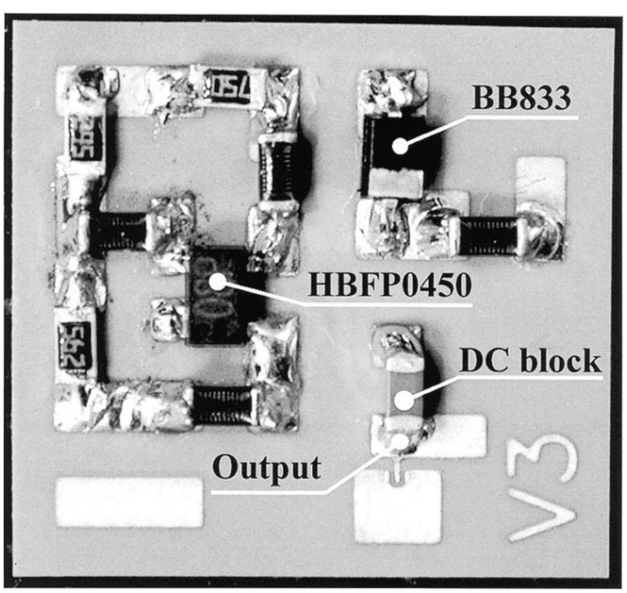

Fig. 4. Top view of the completed LTCC VCO module.

oscillating frequency. The VCO circuit is sent to National Semiconductor Corporation (LTCC Division) for fabrication. Fig. 4 shows the physical view of the constructed VCO module with all the attached components.

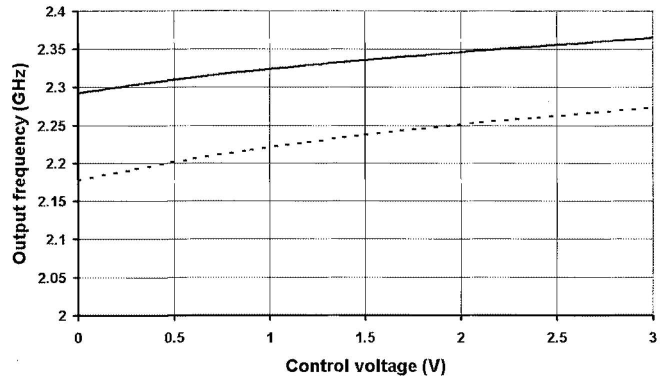

Fig. 5. Measured (solid line) and simulated (dotted line) frequency tuning characteristics.

TABLE I
SUMMARY OF MEASURED VCO PERFORMANCE

Control Voltage (V)	0	1.5	3
Oscillation Frequency (GHz)	2.29	2.34	2.37
Fundamental Power (dBm)	- 7.4	- 3.8	- 0.1
2nd harmonic Power (dBm)	- 59.2	- 53.3	- 50.4
Phase noise @ 100kHz (dBc/Hz)	- 105	- 112	- 121

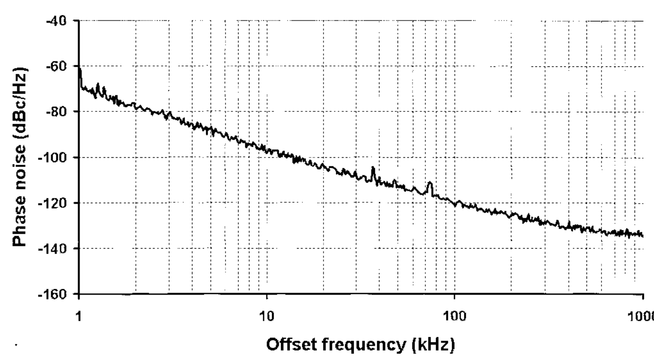

Fig. 6. Measured phase noise spectrum.

III. MEASUREMENT RESULTS

For normal operation, the VCO module is biased at a supply voltage and current of 3 V and 13 mA, respectively ($\mathrm{DC-RF\ efficiency} = 2.5\%$). Fig. 5 shows both the simulated and measured oscillation frequency of the VCO as the tuning voltage is varied from 0 to 3 V. The prototype exhibits a tuning frequency ranging from 2.29 – 2.37 GHz. The measured electrical characteristics of the circuit at different output frequencies are tabulated in Table I for comparison. The results indicate that the harmonic signal is strongly suppressed by the output filter. For illustration, the measured phase noise spectrum of the VCO operating at an oscillating frequency of 2.37 GHz is plotted in Fig. 6. A phase noise level of $-121\ \mathrm{dBc/Hz}$ at an offset frequency of 100 kHz is observed. Phase noise measurement is performed by using HP4352 VCO/PLL Signal Analyzer with noise floor of around -136 dBc/Hz at 100 kHz frequency offset from carrier. Experimentally, the unloaded Q factor of a stand-alone LTCC laminated resonator is found to be 100 ± 20.

IV. Conclusion

The design and construction of a highly integrated 2.4 GHz LTCC VCO module has been described. A total of 8 lumped passives plus the laminated resonator are embedded inside a 15-layer LTCC substrate. The fabricated module exhibits a tuning bandwidth of about 70 MHz and excellent phase noise performance of -121 dBc/Hz at 100 kHz offset frequency. The physical dimension of the module is approximately 12 mm $\times$ 11 mm $\times$ 1.4 mm.

Acknowledgment

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