MICROMACINED FREQUENCY-VARIABLE IMPEDANCE TUNERS USING RESONANT UNIT CELLS

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***Abstract* — This paper presents a new type of micromachined impedance tuners using frequency-variable resonant unit cells. Impedance tuners using resonant unit cells realized by tunable micromachined capacitors showed a wide tuning range equivalent to almost two quadrants of the Smith chart with a high maximum VSWR of 21.2 at Ka-band. Frequency variability is also provided through the use of J-inverters with tunable capacitors. Micromachined tuners are very promising for low-loss tuning of the monolithic circuits as well as accurate noise and power characterization.**

I. INTRODUCTION

Monolithic microwave integrated circuits (MMIC's) are realized by integrating passive components such as transmission lines, resistors, MIM (metal-insulator-metal) capacitors and spiral inductors, together with the active components like MESFET's, HEMT's and HBT's on a single wafer. The capability of batch process is the key to reduce the process cost and enable mass production. However, there are often cases where the fabricated circuits cannot meet the required performance due to the deviation in the process parameters such as layer thickness, doping concentration and so on. It is virtually impossible to correct the values of each component once the fabrication is finished. The tuning elements like the impedance tuner can be very useful for this purpose [1]. With on-chip impedance tuner, the circuit elements can be fine-tuned to meet the desired specifications if necessary. The tuner is also useful for device characterization purposes. For example, FET-based impedance tuner has been developed for noise parameter measurement [2]. Similar tuners can be developed for power applications such as load pull measurement.

The tuners are required to meet the following conditions. First, the impedance tuner should have wide impedance tuning range. Second, the loss of the tuner should be as low as possible to be able to achieve high reflection coefficients. Another useful feature of the tuner is the power handling capability, which is most important when applied to the high-power circuits such as power amplifiers. Conventional tuning elements such as varactor diodes and transistors have shown relatively limited loss characteristics, leading to reduced impedance ranges. The nonlinear characteristics of the semiconductor-based tuning elements also limit their use as high-power tuning elements. Micromachining techniques are most effective in this regard since they are basically conductor structures with very low loss and do not suffer from any nonlinear effects.

In this paper, we propose wide-range frequency-variable impedance tuners fabricated by micromachining techniques. The measured results of the fabricated impedance tuners are presented together the design. In an effort to maximize the tuning range, resonance technique has been employed in the unit cell design. Frequency variability has also been added. To the best of our knowledge, this is the first demonstration of wide-range impedance tuners using MEMS technology at Ka-band.

II. DESIGN OF IMPEDANCE TUNER

Impedance tuner consists of variable components such as varactor diodes and transistors [2]. In this work, tunable metal-air-metal parallel-plate capacitors fabricated by micromachining techniques are utilized as a variable capacitor. It shows 30 % capacitance variation before the top plate of the capacitor is fully deflected. Two types of tunable capacitors were used in this work: shunt and series types.

Since the capacitance variation available from the micromachined capacitor is limited to 30 %, a special technique is needed to extend the impedance tuning range needed for tuner operation. For this purpose, we have employed a resonant unit cell operating near the resonance frequency. The large reactance change near the resonant frequency makes it possible to obtain a relatively large impedance variation.

A. Fixed-Frequency Tuner using Shunt Resonant Cells

In this work, two kinds of impedance tuners are designed and fabricated. The first design is a fixed-frequency tuner shown in Fig. 1, which is implemented by the transmission line loaded with two shunt resonant cells consisting of a micromachined shunt-type variable capacitor and a high-impedance short-circuited line operating as a grounded inductor. The fixed-frequency tuner synthesizes the impedance on the Smith chart by tuning the capacitance of the shunt resonator with the tunable capacitors, C_a and C_b. The tuning range of this tuner is targeted for noise matching the transistors.

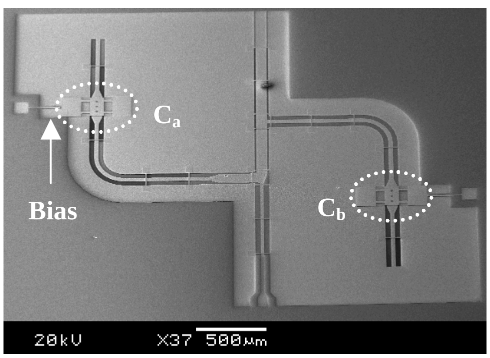
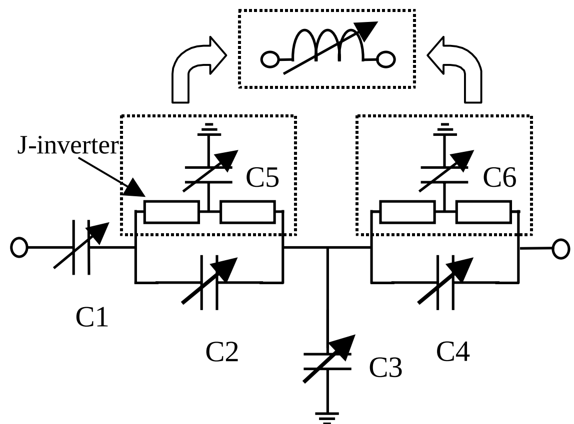


Fig. 1 Photograph of the fixed-frequency tuner

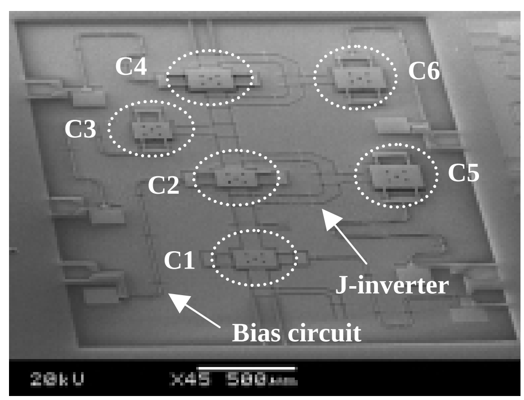
B. Frequency-Tunable Tuner using Resonant Cells with J-Inverters

Even though the resonance-type tuners show a wide impedance range, the operating bandwidth turns out to be very narrow. In order to solve this problem, additional frequency tuning element is added in the unit cell to change the resonant frequency of the resonator itself. Variable inductors, which are hard to implement in monolithic forms, would be needed for frequency tuning. In this work, an artificial tunable inductor has been synthesized by using a circuit consisting of a shunt tunable capacitor between two J-inverters [3-4]. It is then possible to move the resonance frequency with this artificial variable inductor.

The frequency tunable impedance tuner is shown together with a circuit schematic in Fig. 2. It consists of two frequency-tunable parallel resonant cells and two tunable capacitors (C1 and C3). The series capacitor, C1 effectively changes the angle of the reflection coefficient while the parallel resonance cells change the magnitude of the reflection coefficients. Frequency tuning of the resonance cells is achieved by changing the capacitance, C2 and C4, together with the effective inductance with C5 and C6 sandwiched between J-inverters. The bias circuit to each tunable capacitor is implemented with a quarter-wave length line and an MIM capacitor. This impedance tuner is designed to synthesize the impedances in the 2nd and 3rd quadrants of the Smith chart for use in the optimum load measurement for power transistors. The chip sizes of the fixed-frequency tuner and frequency tunable tuner are $3.2\times2.7mm^2$, $3.7\times2.0mm^2$, respectively.



(a)



(b)

Fig. 2 The frequency-tunable tuner
(a) schematic and (b) photograph

Commercial circuit simulator, HPADS and EM simulator, IE3D have been used in the tuner design and analysis. Full-wave analysis has been performed for accurate prediction of tunable parallel-plate capacitors and discontinuities in CPW.

III. FABRICATION OF IMPEDANCE TUNER

The impedance tuners were fabricated on a 520μm-thick quartz substrate using surface micromachining technology. The CPW lines, MIM capacitors and overhanging structures such as variable parallel-plate capacitors and air bridges are formed using the gold electroplating process and subsequent releasing technique.

At first, titanium and gold layers are thermally evaporated on the substrate as the seed layer for gold electroplating. The 3.5 μm-thick electroplating mold is patterned with photoresist, through which the CPW transmission lines and bottom plates of the parallel-plate capacitors are electroplated. After electroplating of the first metal, 0.2 μm-thick dielectric layer is deposited for insulating layer of the capacitors. The photoresist sacrificial layer is spin-coated with the height of 1.8 μm and patterned by UV lithography. The patterned sacrificial layer is thermally cured for reflowing the edge of the photoresist. By curing photoresist, it is chemically stabilized and not affected by the next fabrication steps. Thanks to the shape of reflowed sacrificial layer, the top plate of tunable capacitor shows the curved anchor support, which also facilitates the subsequent electroplating steps. Next, the seed layer is evaporated and followed by electroplating of the second metal layer with the thickness of 2 μm for the top plates of the variable capacitors, MIM capacitors and air-bridges. Finally, by removing the sacrificial layer using plasma ashing process, the overhanging structures suspended over the bottom metal layer can be obtained.

IV. EXPERIMENTAL RESULTS

The measurement of the fabricated impedance tuners was performed by on-wafer probing using HP 8510C Network Analyzer.

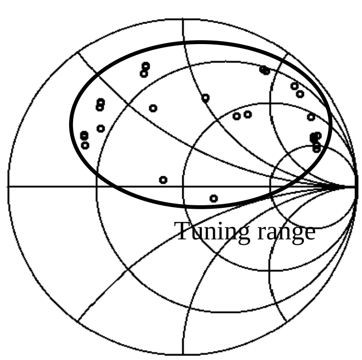
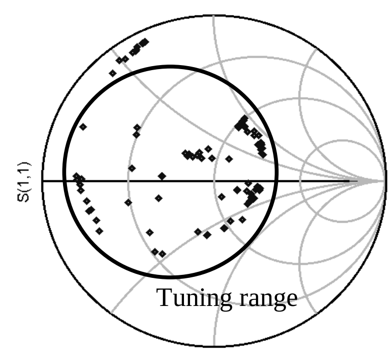


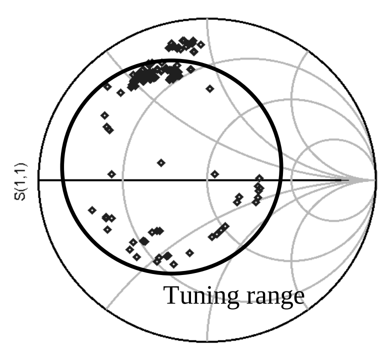
Fig. 3 Measured constellation of fixed-frequency tuner (frequency = 29GHz)

Measured constellation of the impedance points synthesized by the fixed-frequency tuner is shown in Fig. 3. The measurement frequency is 29 GHz. It can be seen that the use of the micromachined tuner allows high values of reflection coefficient to be synthesized over the 1st and 2nd quadrants of the Smith chart.

Measured constellation of the impedance points synthesized using the frequency tunable tuner is shown in Fig. 4. As shown in the measured results of Fig. 4(a), the frequency tunable tuner operating at 25 GHz is capable of generating the impedances in the 2nd and 3rd quadrants of the Smith chart, which correspond to the optimum load range of the power transistors. To show the frequency variability, the values of C5 and C6 have been adjusted to shift the resonant frequency from 25 to 23.5 GHz. The constellation of the impedance points measured at 23.5 GHz is shown in Fig. 4(b). Impedance range comparable to that at 25 GHz was observed, demonstrating the frequency tunability. The maximum applied bias voltage for driving the tunable capacitor was 40V.



(a) frequency = 25GHz



(b) frequency = 23.5GHz

Fig. 4 Measured constellation of frequency-tunable tuner (a) before frequency tuning (b) after frequency tuning

In table 1, measured VSWR data of the two impedance tuners of this work are compared with other reported tuner data using HEMT switches. It can be seen that the micromachined impedance tuners exhibit superior VSWR to the conventional tuners using FET's, which is attributed to the low-loss nature of the micromachined components. The table clearly shows the advantage of the micromachined tuners.

Tuner type	VSWR	Frequency	Ref.
Frequency fixed tuner	14.4	29GHz	-
Frequency tunable tuner	21.2	25GHz	-
HEMT tuner	6	27GHz	[1]
HEMT tuner	12.3	18GHz	[2]

Table 1. Comparison of measured VSWR with other reported data

V. CONCLUSIONS

In this work, resonant-type impedance tuners are designed and fabricated with micromachining techniques. Even with the limited capacitance variations available from the micromachined tunable capacitors (~30%), a wide tuning range was achieved with the help of the resonant unit cells. The narrow bandwidth of the resonant-type tuners has also been alleviated by employing tunable unit cells realized by artificial tunable inductors using J-inverter and tunable capacitors. Measured micromachined tuners showed a wide tuning range equivalent to almost two quadrants with a high maximum VSWR of 21.2. This VSWR is far greater than that of the comparable tuners using HEMT devices. Micromachined tuners are very promising for low-loss/high-Q tuning of the circuits, as well as for accurate noise and power measurements at mm-waves.

VI. ACKNOWLEDGMENT

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REFERENCES

[1] W. Bischof, "Variable Impedance Tuner for MMIC's," *IEEE Microwave Guided Wave Lett*., vol.4, pp.172-174, June, 1994.
[2] C. E. McIntosh, R. D. Pollard, and R. E. Miles, "Novel MMIC Source-Impedance Tuners for On-Wafer Microwave Noise-Parameter Measurements," *IEEE Trans. Microwave Theory Tech*., vol.47, pp.125-131, Feb., 1999
[3] Jeffrey H. Sinsky and Charles R. Westgate, "Design of an Electronically Tunable Microwave Impedance Transformer," in *IEEE MTT-S Int. Microwave Symp. Dig*., 1997, pp.647-650.
[4] G. Matthaei, L. Young, E.M.T. Jones, Microwave Filters, Impedance-Matching Networks, and Coupling Structure, Dedham : Artech House, 1980, pp.434-438.