Effects of Bonding-wire Interconnect on Electrically Tunable Microstrip Antennas

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***ABSTRACT* — The objective of this paper is to discuss bonding-wire effects on microstrip antennas for miniaturization and tuning of the resonant frequency. When varactor diodes are used as capacitive loads for the antenna, it allows reducing the size of the antenna with an added feature of tunability. Change of resonant frequency of microstrip antenna is also affected by inductance of bonding- wire, which is used for assembly in this work. Varactors and bonding-wire inductance are characterized by their equivalent circuits and incorporated as lumped elements in the Finite Difference Time Domain method. The reactive loading of bonding-wire has a large significant effect on the resonant frequency of microstrip antenna. The inductance of bonding-wire shifts resonant frequencies of microstrip antenna to be shifted to lower values but the tuning range is not affected. The size reduction and tunability of the antenna are demonstrated experimentally and theoretically using varactor and bonding-wire interconnects.**

I. INTRODUCTION

The physical size of the radio communication components on which antennas are installed has been scaled down in the recent years, especially in mobile communications. Therefore, there is a demand for small size antennas with efficient electrical performance. In addition to the miniaturization, another desirable characteristic of modern antennas is the wide-band operation, which requires a single antenna to satisfy the frequency band requirements of different applications. To meet the these requirements, microstrip antennas are the most suitable configuration due to their smaller size, lightweight, low cost and ease of fabrication and integration with RF devices. A common technique for the miniaturization and wide band of microstrip antennas is reactive loading. Reactive loading also enables the tuning capability of the antenna. By changing the level of loading, resonance frequency of the microstrip antenna can be tuned over a wide range without significant variations in the antenna performance. As an electrical loading element, the varactor diode is widely used and implanted in the substrate between the patch and ground plane. This processing requires a drilling of substrate, and thus it makes the assembly complex. The bonding-wire interconnection can be considered as an attractive connection method because of its easy implementation and low cost. However, The reactive loading of bonding-wire will make a large effect on the resonant frequency of microstrip antennas.

In this paper, the characteristics of a varactor loaded microstrip rectangular patch antenna and effects of bonding-wire on its performance are investigated. Varactor diodes are loaded between patch and ground plane through via holes using bonding-wire interconnects. They are placed at the corners of the patch to maximize its tuning effect since the electric fields are maximized at those points. The resonant frequency variation of microstrip antenna by varactor and bonding-wire interconnect is studied experimentally and theoretically using full-wave Finite Difference Time Domain (FDTD) method.

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II. VARACTOR LOADED AND WIRE BONDED MICROSTRIP ANTENNA

The use of varactor diodes to improve the bandwidth of a microstrip patch antenna was first reported by P. Bhartia and I. J. Bahl [1]. The equivalent model of microstrip antenna can be represented by a simple *RLC* tank model [2]. A varactor is generally used as an element to change the reactance of microstrip antenna so that the resonance frequency of a microstrip antenna can be varied inverse-proportionally to the square root of the capacitance value. A varactor is a semiconductor junction diode with a non-linear reverse-bias capacitance. The capacitance-voltage characteristic is governed by the applied voltage and the parameters of the junction. The capacitance of the varactor decreases with the increasing reverse bias voltage [3]. Placing a varactor between the patch and ground plane is equivalent to voltage-controlled capacitor being put parallel to the *RLC* tank circuit of microstrip antenna. By changing the reverse bias voltage, capacitance of the diode will be changed and thus tank circuit will be tuned to the lower resonant frequency.

The varactor used here is an unpackaged GaAs FET diode by connecting the source and drains of a GaAs FET together to form a diode. The equivalent circuit and values of parameters are shown in Fig. 1. It consists of an interconnect inductance *Lp*, junction capacitance *Cg*, and a series resistance *Rs* including contact resistance. To account for the conductance properties, such as generation-recombination current, of the Schottky-diode, a resistance *Rp* is included in parallel with *Cg*. FET diode varactor is connected to the microstrip antenna using boding-wires. A single bonding-wire interconnect can be simply treated as a single-stage low-pass filter with a fixed cutoff frequency. It consists of a series lossless inductor *L* and a parallel capacitor C between bonding-wire and ground plane. These inductance and capacitance of bonding-wire will change the resonant frequency and should be included in the modeling for simulation.

II. DESIGN AND FDTD ANALYSIS

Initially, the size of reference patch is designed by the transmissionline model and then rigorous FDTD method is applied to get the accurate analysis of the antenna. The theoretical characteristics are calculated using the FDTD method and all the lumped parameters of the varactor diode and the bonding-wire are taken into consideration.

The microstrip antenna without varactors is designed for the operating frequency of approximately 4.2 GHz. It is designed on Duroid substrates with $e_r = 2.33$ and the thickness is taken as 0.7873 mm. Using design equations [4], the length of the patch is found 23.2 mm and the width of the antenna is taken as 15.9 mm. Varactors are characterized by their equivalent circuits and incorporated as lumped elements in the FDTD method [5]. Conductors of the antenna are assumed to be perfectly conducting and have zero thickness. Dielectric of the antenna substrate is lossless. Moreover, The ground plane and the dielectric are considered to be infinite. The computational domain is shown in Fig. 2. The main discretization parameters are dx= 0.3975 mm, dy=0.19685 mm, and dz=0.4 mm. The diodes are placed at the four corners of the patch to maximize its tuning effect since the electric fields are maximized at those points [6]. Although FET diode is actually connected with the microstrip antenna on the same surface using boding wire, varactor diodes are directly mounted between patch and ground plane in simulation. To embed the effect of bonding-wire into FDTD simulation, the bonding-wire can be simply analyzed as a single series inductance because of small parallel capacitance. Errors in placement of the patch and variations in wire bonding process result in wide variations in bonding-wire lengths and produce a difficulty in its modeling. However, the geometric dimensions of bonding-wire can be approximately determined by layout dimensions and reasonable assumptions. The inductance is calculated about 4 nH using static conformal mapping approach [7]. It is assumed in calculation that diameter of bonding-wire is 0.025 mm, height is 0.3 mm, and length is between 2.5 mm and 3 mm.

III. RESULTS

In fabrication, varactors are placed near to four corners of patch by connecting to patch with bonding-wire in Fig. 3. All the measurement data were obtained using HP8510 Network analyzer.

In the case of the reference microstrip antenna without varactor, the first resonant frequency is at the 4.2 GHz and the second resonant frequency is at the 5.8 GHz. In Fig. 4 ~ 6, the measured resonant frequencies of the microstrip antenna with bonding-wire inductance are also in good agreement with the simulations. A tuning range of 46% around a center frequency of 2.75 GHz was achieved. Meanwhile, the tuning range of the second resonant frequency centered at 4.86 GHz is very small, about 6.7 %. The magnitude of return loss does not agree well with the simulation due to the $\lambda/4$ transmission line, used for matching in the fabricated structures. Fig. 7 emphasizes the importance of accurately incorporating the inductance of the bonding-wire. The upper group of characteristics shows the change of the second resonant frequency in response to different capacitances. The bottom group of lines depicts the change of the first resonant frequency. The center frequencies are 2.71 GHz and 3.05 GHz respectively for simulation with 4nH bonding-wire and simulation without bonding-wire. In both cases, tuning ranges are almost same, about 43% and the two resonant frequencies decrease with similar amounts as the capacitance increases.

Significant error in the resonant frequency is observed when the bonding-wire inductance is not properly evaluated. The inductance of the bonding-wire is added into the inductance of antenna and increases an effective inductance of the LC tank of microstrip antenna. Therefore, the resonant frequencies of microstrip antenna are shifted to lower values but its tuning range is not changed.

IV. CONCLUSION

This paper analyzes and evaluates the use of varactor diodes and the effects of bonding-wire on the resonant frequency of the microstrip patch antenna. A full-wave finite difference time domain method is used to investigate the characteristics of microstrip antennas. The effects of bonding-wire are also included in the simulation.

The varactor loaded microstrip antennas exhibit quite practical antenna characteristics, indicating that it is feasible to use varactor diodes to reduce the antenna size, and also to tune the antenna over a wide band. Shifting of the resonant frequency due to bonding-wire inductances has a positive effect on miniaturization of microstrip antenna. Considering the radiation characteristics, higher cross-polarization may be introduced by parasitic and non-symmetric components of bonding-wire, originate from non-repeatable assembly. In this research, the bonding-wire is modeled using lossless LC tank circuit, but more accurate model for higher frequency should be adapted to include resistive losses due to skin depth and radiation loss due to bonding-wires.

ACKNOWLEDGEMENT

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Vbias [V]	0	-0.5	-1
Cg [pF]	1.62	1.15	0.324
Lg [pH]	148	77.6	70
Rg [Ω]	3.75	10.5	12
Rp [Ω]	1.57 k	1.2 k	0.8 k

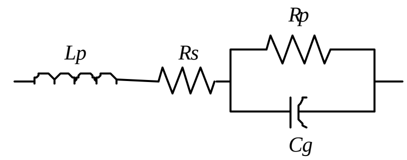

Fig. 1 Equivalent circuits and parameter values of GaAs FET diode

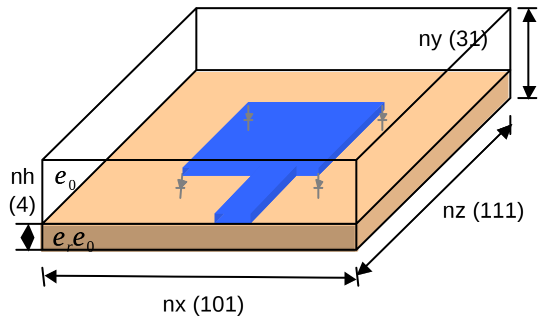

Fig. 2 Computational domain for FDTD simulation

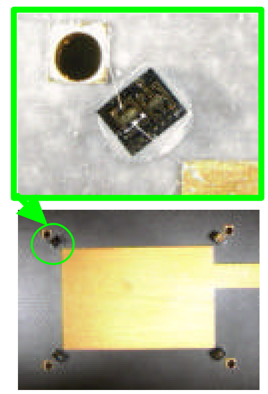

Fig. 3 Fabrication

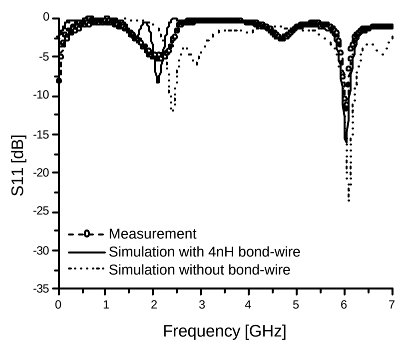

Fig. 4 S_{11} of antenna at Vbias=0V

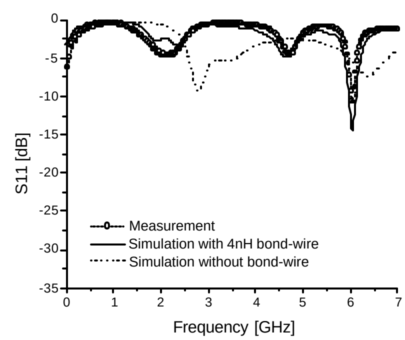

Fig. 5 S_{11} of antenna at Vbias=-0.5V

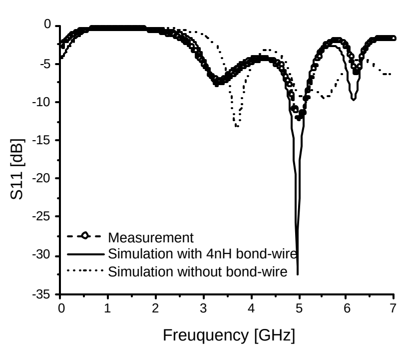

Fig. 6 S_{11} of antenna at Vbias=-1 V

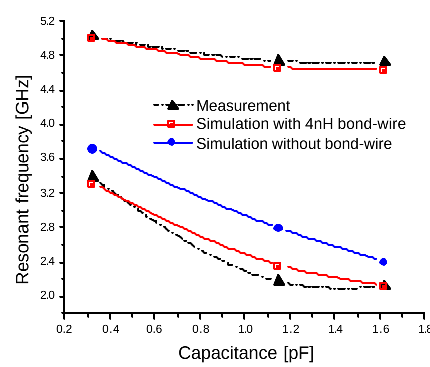

Fig. 7 Change of resonance frequency due to bonding-wire