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Radiation Efficiency Enhancement for Dipoles Placed Adjacent to Lossy Silicon Substrates

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Abstract—Radiation efficiency of a dipole antenna is discussed when placed closely to a 0.11 × 0.11 λminimizing the current excited inside the silicon substrate. The use of a small-size floating metal layer underneath the silicon wafer is proposed for efficiency improvement. The total antenna area with the silicon wafer is 0.13 × 0.2 λ2. Co- and cross-polarized radiation patterns in H and E planes are measured with the silicon wafer placed 0.003 λe away from the dipole. Full-wave simulations reveal that placing the floating metal layer underneath the lossy silicon substrate increases the total radiated power by approximately 2×. This is validated experimentally by fabricating 3.5-GHz FR4 dipoles next to lossy silicon substrates with and without the aforementioned floating metal. Measured radiation patterns are presented for both cases and result in extracted radiation efficiencies of 72% (floating metal present) and 43% (no floating metal).

I. INTRODUCTION

On-chip antennas are often viewed attractive for single-chip wireless systems due to their compactness, low-cost, and high integration level. Such antennas, however, typically suffer from low radiation efficiency (<5%) due to their proximity to lossy substrates including CMOS-grade silicon [1], [2]. High radiation efficiency solutions are highly desirable for wireless transceivers that aim to long battery life and low noise figure. Possible implementations include antennas fabricated in IC packages. For example, a patch antenna in a ceramic ball grid array package is presented [3], whose simulated radiation efficiency is 63% at 5.52 GHz. An antenna fabricated in an LTCC package is also introduced [4], which consists of a main rectangular patch and a U-shaped parasitic element. Both antennas require an additional cavity layer between the top antenna and the bottom ground layers with thickness of a few mm (for operation around 5 GHz) for acceptable radiation performance.

In this paper, a half-wavelength thin FR4 dipole antenna placed in close proximity to a low-resistivity silicon wafer without additional layers is investigated as an attractive alternative. In order to reduce efficiency deterioration due to the antenna’s proximity to the lossy substrate, we propose to place a small-size floating metal underneath the silicon wafer. This metal layer significantly improves the radiation efficiency by minimizing the current excited inside the silicon substrate.

II. A HIGH-EFFICIENCY ANTENNA DESIGN WITH LOW-RESISTIVITY SILICON

A. Antenna efficiency investigation with lossy silicon substrate

A dipole antenna consists of two quarter-wavelength thin lines and a center feed fabricated on an FR4 layer with dielectric constant of 4.4 and loss tangent of 0.02. An ideal differential feed is utilized in exciting the antenna in HFSS. A 10-Ω-cm silicon wafer is located near the dipole with a thickness of 200 μm and size of 7 × 7 mm2 or 0.11 × 0.11 λ2. The efficiency of a straight center-fed dipole is primarily determined by its distance to the silicon substrate (d) and the vertical distance s between the feeding point and the center of the silicon substrate (Fig. 1). When s = 0 and d = 0.2 λe the simulated radiation efficiency is 96% at 3.5 GHz. Even when d is reduced to only 0.003 λe, the dipole still maintains radiation efficiency of 90%. However, the situation changes when s is increased from 0 to 0.2 λe (d = 0.003 λe). Since electric-field radiation mostly occurs at the edges of the dipole, the radiation efficiency is reduced from 90% to 70% in this case. This is important to consider when trying to reduce the form factor of the dipole by bending it around the silicon substrate. In this case the distance between the dipole edges and the silicon substrate is denoted by g (Fig. 1). When g is reduced from 0.2 λe to 0.003 λe, the simulated radiation efficiency dramatically decreases from 90% to 20%.

B. Floating metal for enhanced antenna efficiency

In order to prevent power from being dissipated in the silicon wafer, we propose to place a small-size floating metal...
plate underneath the silicon wafer (Fig. 2). Because of the near-zero impedance of the metal, most of the induced current from the dipole flows on the metal instead of the lossy silicon substrate. This also leads to a reduced antenna input impedance. The distances \(d\) and \(s\) are fixed to 0.003 \(\lambda_e\) and 0, respectively for this design. As \(g\) varies from 0.003 \(\lambda_e\) to 0.02 \(\lambda_e\), the radiation efficiency of the design that includes the floating metal is nearly 2 \(\times\) higher than that of the design without the metal. For example, when \(g = 0.003 \lambda_e\) the antenna efficiency improves from 20\% to nearly 50\%.

The radiation efficiencies extracted from the radiation patterns are 72\% and 43\% for the dipole with and without the floating metal respectively. These values are slightly higher than the ones obtained with the ideal differential feed due to potential radiation from the unbalanced feed.

III. ANTENNA FABRICATION AND MEASUREMENTS

A bent dipole antenna is fabricated on FR4 with the same material parameters as simulation. A 10 \(\Omega\cdot\text{cm}\)-resistivity silicon wafer is attached 0.003 \(\lambda_e\) away from the dipole. The overall antenna size is about 0.13 \(\times\) 0.2 \(\lambda_e^2\). Unlike our simulations, a non-ideal slot-line feed without a balun is utilized in these measurements causing unwanted radiation from the feed. However, the feed-line length is sufficiently short to clearly show the radiation efficiency improvement caused by the floating metal. Three different antennas are fabricated and tested: a) a bare dipole (no silicon wafer), b) a dipole next to a silicon piece and c) a dipole next to a silicon piece with a copper plate underneath it. The bent dipole with the floating metal requires a matching circuit formed by a 1 nH inductor in parallel. The measured return loss of the bare dipole is -8 dB at its resonant frequency. This is reduced to -20 dB at 3.5 GHz for the dipole with the silicon piece. This is caused by additional power dissipation in the silicon wafer. When the floating metal is introduced, the return loss becomes -25 dB at 3.1 GHz with the aforementioned external shunt inductor (Fig. 3).

A receiving horn antenna with a gain of 11 dBi placed 2.5 m away from the dipoles is employed for the radiation pattern measurements. The measured \(H\)- and \(E\)-plane radiation patterns are quite similar to the simulation results. Fig. 4 shows the normalized co-polarized patterns in both planes. The amount of radiated power from the dipole with the silicon wafer is smaller than that from the bare dipole. When the floating metal is added, the radiation patterns are nearly identical to the bare dipole and the total amount of power is approximately twice as large than the dipole with only silicon.

IV. CONCLUSION

Radiation efficiency of a dipole antenna in close proximity to a lossy silicon wafer has been discussed. By simply adding a floating metal underneath the lossy substrate, the radiation efficiency can be increased by almost 2 \(\times\). This approach provides a promising solution for high-efficiency wireless systems with microwave and millimeter-wave integrated circuit transceivers.

REFERENCES