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High Impedance Layer for CMOS On-chip Antenna at Millimeter Waves

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***Abstract*—The application of high impedance layer (HIL) in (Bi)CMOS millimeter wave on-chip antennas is studied. The HIL consists of grounded two-dimensional periodic dogbone-shaped elements that use a metal layer of the CMOS structure. Two different mechanisms that take advantage of the HIL in on-chip antenna design are investigated. First, we implant the HIL below the on-chip dipole antenna to act as an artificial magnetic conductor (AMC), which enhances the radiation of the dipole. We have obtained 1.2 dB realized gain for a dipole antenna placed above a 4×5 dogbone array at 90 GHz. The second use of the HIL is directly as a radiating antenna, without the need of the dipole antenna on top. In this case we have obtained -2dB accepted gain from a HIL made of 5×5 dogbone array, fed by two microstrip lines having 180º phase difference. The results are obtained by full-wave simulation.**

Keywords-on-chipantenna, CMOS, millimeter wave, leaky wave antenna, leaky mode, high impedance layer, AMC

I. INTRODUCTION

The development of monolithic millimeter-wave (MMW) systems has been growing rapidly in the last decade. Several applications have been proposed including 60GHz wireless local area networks (WLANs), 79 GHz automotive short-range radar, 94GHz and 140 GHz passive imaging system, and high data rate communications. As wavelengths shrink to millimeter lengths at MMWs, on-chip antennas could be a good solution to relieve interconnection loss issues and improve cost/scale performance. Among most of the designs in the literature, silicon based processes, e.g., silicon-germanium, are the mainstream platform for on-chip antennas because of their low cost and high integration capabilities. In [1-3], on-chip antennas were designed based on dipole, folded dipole, slot, inverted F geometries, with radiation off (orthogonal to) the chip. All these antennas have the same drawback, since they radiate mainly in the low resistivity substrate, they result in extremely low antenna gains and efficiencies at MMW frequencies. For example, the 140 GHz on-chip antenna implemented in 65 nm CMOS by [4] has a gain of only -25 dB. However, for future applications of MMW TRXs with on-chip antennas, such as MMW imaging and multi-gigabit-per-second short range wireless communications, it is strongly desirable to achieve high efficiency antennas, which would lead to integrated transmitters and receivers with efficiency much higher than the current state of the art.

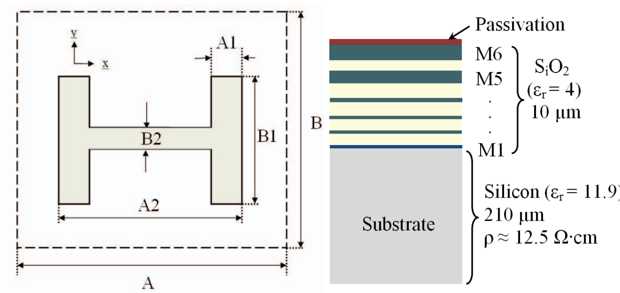

Fig. 1. (a) Unit cell of dogbone shaped element (b) Cross section (lateral) view of CMOS chip environement with six metal layers over the silicon substrate.

In recent years, high impedance surfaces and high impedance materials [5] have been used to realize low profile antennas [6], antennas lying horizontally on a thin artificially engineered substrate. The most common substrate design is based on the "mushroom" structure on a metallic ground plane (MGP) [5, 7]. This structure is based on having mushroom like resonator cells. Because of the very low thickness constraint in the (Bi)CMOS metal layers, this mushroom-like structure would have an extremely small thickness and extremely short via, and thus, it may not be the most suitable geometry for CMOS integration. Especially in the case of a ground plane under the silicon substrate, since through-substrate vias are not part of the standard (Bi)CMOS process. Another type of high impedance surface, based on planar arrays of dogbone shaped (i.e., H-shaped) metallic conductors [8-9] as shown in Fig. 1(a), does not need a continuous MGP, which makes it easy to be implemented in CMOS environment.

In this paper, we make use of a high impedance layer (HIL) for an on-chip antenna design, by using two different approaches. First, the HIL composed of periodic dogbone-shaped conductors above a ground plane is placed below an on-chip dipole antenna to act as an artificial magnetic conductor layer or as a high impedance surface. Based on the initial dimensions obtained from an approximated formula in [9], numerical simulations are utilized to optimize the dimensions of dogbone elements in a given frequency band, and to simulate the performance of whole antenna structure.

In the second approach, the HIL is made by a dogbone array over a ground plane in M1, and fed directly as radiators, without the need of an antenna on top.

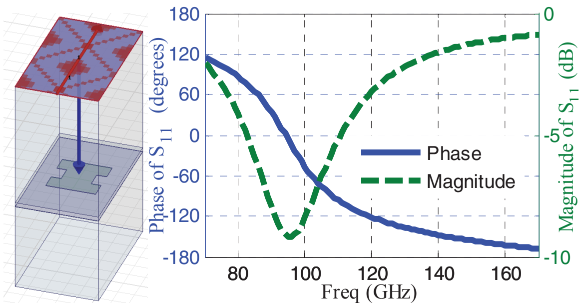

Fig. 2. (a) Plane wave incidence ground-backed unit cell of dogbone with periodic boundary (b) Phase and magnitude of the reflection coefficient at the surface of the HIL made of dogboness over a ground plane.

Fig. 1(b) illustrates the side (lateral) view of a chip environment used in this paper. The total thickness between top metal layer (M6) and bottom metal layer (M1) is around 10 µm. The silicon substrate has the thickness of 210 µm with the dielectric constant of 11.9 and resistivity of 12.5 Ω·cm.

II. ON-CHIP DIPOLE ANTENNA ABOVE A HIL

In [9], it was shown that this HIL composed of periodic dogbone elements possesses a magnetic resonance. While it is operating near the magnetic resonance frequency, the HIL is acting as an artificial magnetic conductor (AMC) whose condition is characterized, assuming low losses, by a vanishing phase of the reflection coefficient for a plane wave with orthogonal incidence. According to the image principle, placing a horizontal source current over a perfect magnetic conductor (PMC) induces an image current having the same direction as the source current on the other side of PMC, which inherently enhance the antenna radiation.

The equivalent circuit model in [9] provides an approximate method to calculate the magnetic resonant frequency of a grounded dogbone. And the results here are optimized with full wave simulations by HFSS. Fig. 2(a) illustrates the simulation setup of plane wave incidence over a HIL made by a ground-backed infinite array of dogbones. Periodic boundary conditions are applied in the simulation. It should be noted that the dogbones are placed on M5 while the ground is assumed to be below the silicon substrate as labeled in Fig. 3(b). The phase and magnitude of the plane wave reflection coefficient are shown in Fig. 2(b). The dimensions of the dogbones are optimized to make the zero-phase reflection occur at 94 GHz, which is very close to the HIL's magnetic resonance frequency. It can also be seen that at 94 GHz, the magnitude of reflection coefficient has its minimum value. It is because at the magnetic resonance the current is maximum which induces maximum ohmic loss. The optimized dimensions of the unit dogbone element are as follows, A = 0.4 mm, B = 0.25 mm, A1=50 µm, B1= 150 µm, A2 = 150 µm, and B2 = 90 µm.

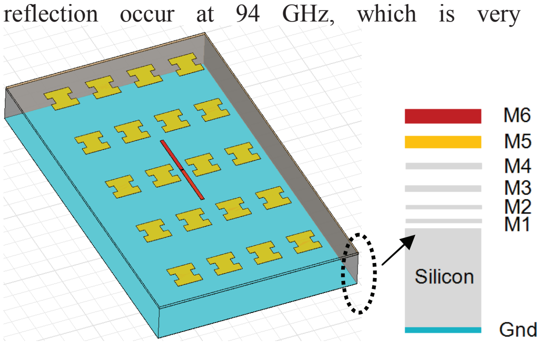

Fig. 3. (a) Dipole over a HIL composed by dogbones. (b) Side (lateral) view.

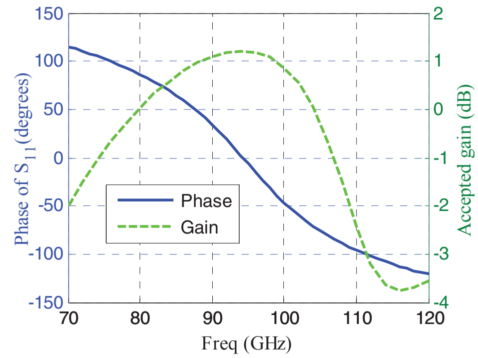

Fig. 4. Accepted gain at broadside ($\theta = 0°$) of dipole antenna above grounded dogbone layer and phase of reflection as in Fig. 2.

Fig. 3 shows the configuration of a dipole antenna above a HIL made of a ground-backed dogbone array. The dimensions of the dogbones are as in Fig. 2. The dipole antenna is on the topmost metal layer-M6 while the dogbone layer is on M5. These two layers, M5 and M6, are used because they are thicker than the others, which means less conduction loss. Below the silicon substrate, it is assumed that there is a ground plane, which in practice could be realized by paint, an interconnection layer in the chip package or in the printed circuit board (PCB). The total area of the proposed antenna is 2 mm × 1.2 mm. The dipole length is 660 µm, which is designed to match the ideal 50 Ω lump port around 90 GHz.

Fig. 4 shows the accepted gain of the dipole over the HIL shown in Fig. 3 versus frequency. To be instructive, the phase of reflection in Fig. 2 is plotted together so as to compare with the gain's dependency over frequency. It can be observed that at the magnetic resonant frequency (94 GHz), the gain reaches its peak value, 1.2 dB, which, considering the losses in the chip environment, shows that this design provides a good gain. Fig. 5(a) shows the accepted gain pattern in the E and H planes of the dipole antenna in Fig. 3 at 94 GHz. Due to the perfect symmetry of simulated structure, the gain pattern is also symmetric in both the E and the H planes. The antenna input reflection coefficient is plotted in Fig. 5(b). The 10dB input impedance bandwidth is 12GHz, from 85 GHz to 97 GHz.

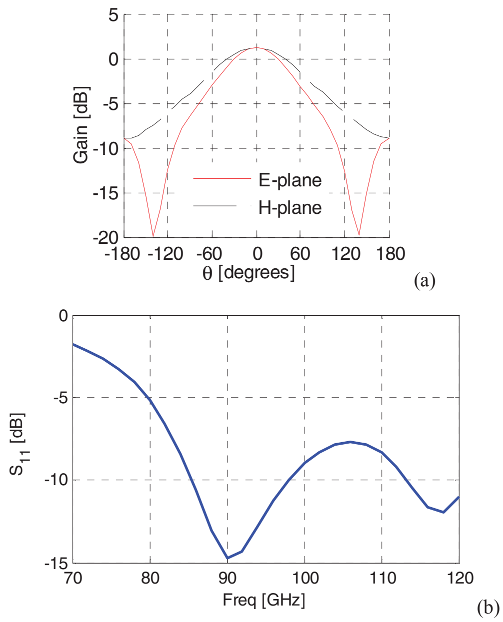

Fig. 5. Dipole over the HIL. (a) Gain patterns at 94 GHz. (b) Antenna input reflection coefficient.

III. ON-CHIP ANTENNA MADE BY A HIL WITHOUT DIPOLE ON TOP

The design of the HIL on-chip antenna begins with a plane wave incidence simulation to find the dimensions of each dogbone that exhibits a resonant frequency at 140 GHz. This frequency is very close to the magnetic resonance. Differently from the previous case in Sec. II when the HIL is placed below a dipole, here the ground plane is set at M1, which is the bottom layer of CMOS structure, whereas dogbones are placed at M6. One great advantage of using M1 as ground plane is that it shields the wave from penetrating into the lossy substrate and meanwhile reduces the coupling between antenna and other RF front end circuitry. The dimensions of the unit dogbone element are as follows: A1=50 µm, B1= 150 µm, A2 = 250 µm, and B2 = 20 µm. The periods between adjacent dogbone are A = 260 µm and B = 160 µm.

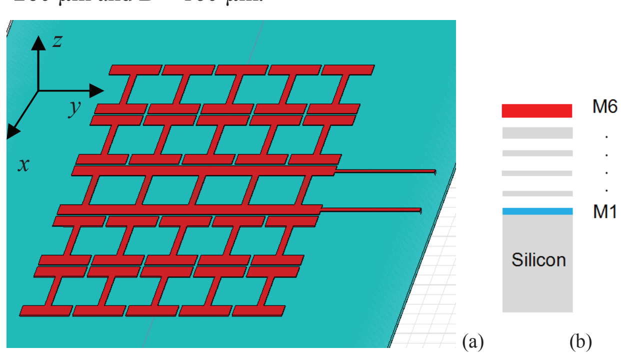

Fig. 6. (a) 5×5 dogbone array with center row connected and fed by two inverse phased 50 Ω microstrip from one side. (b) Side (lateral) view. The ground of the HIL is at M1.

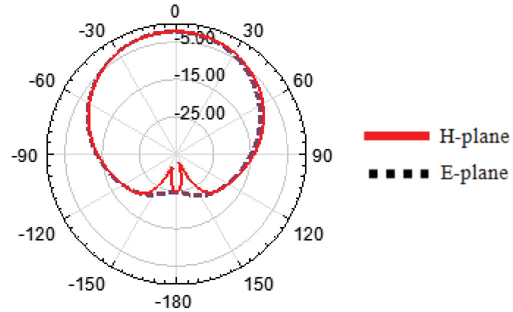

Fig. 7. Accepted gain pattern in the E and H-planes for the HIL antenna (without dipole on top) in Fig. 6.

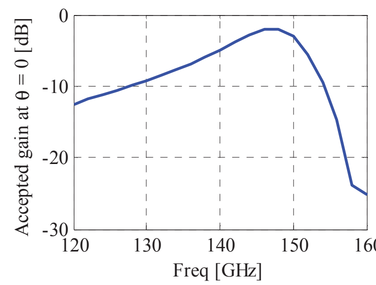

Fig. 8. Accepted gain at broadside direction ($\theta = 0°$) versus frequency for the HIL made by the 5×5 dogbone array in Fig. 6 fed by two inverse phased 50 Ω microstrip from one side. The HIL does not have a dipole on top.

Fig. 6 shows a practical design of the HIL antenna made by an array of 5×5 dogbones with the same dimensions and periods as discussed above. To alleviate the effect of four side rows and enhance the gain at broadside, the center column of dogbones are physically connected along the y direction. The HIL dogbone array is fed by two 50 Ω microstrip lines from one edge, with inverse phase, which is similar to differential signal feed. The accepted gain pattern in Fig. 7 shows that the antenna is directive at broadside and the gain is negative due to considerable ohmic loss at MMWs and especially because of the extremely small thickness h. The accepted gain at broadside of this antenna is plotted versus frequency in Fig. 8. It can be observed that the peak gain for the proposed HIL 5×5 dogbone array is around -2 dB and appears at 145 GHz, which is close to the magnetic resonant frequency of each dogbone. Preliminary results of the antenna input impedance in Fig. 9 show a flat curve between 140 GHz to 150 GHz, with the input resistance close to 25 Ω. These results show the possibility to match the antenna..

Finally we would like to conclude with the observation that in [10], an in-plane mode analysis of planar layer formed by arrayed pairs of metallic dogbone separated by a thin dielectric layer was carried out. It was reported that along the dogbone alignment direction, a TM_0 improper leaky mode, supported by an anti-symmetric current distribution, occurs at a frequency in the proximity of magnetic resonance. Because of the image principle, an anti-symmetric current distribution in a layer of thickness H of dogbone pairs is equivalent to a current distribution in a single layer of dogbones at a distance $h = H/2$ from a ground plane. This means that a leaky mode could be excited in a HIL at a frequency close to the magnetic frequency.

In other words, a HIL could also radiate as an antenna because a leaky mode is excited when some elements of the HIL are fed.

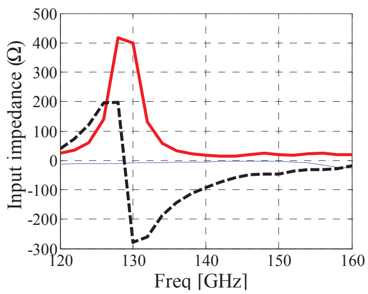

Fig. 9. Input impedance of the HIL antenna in Fig. 6 versus frequency.

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