Probe Modeling for Millimeter-Wave Integrated-Circuit Horn Antennas

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Abstract — **Integrated-circuit probe-excited horn-antenna arrays etched in silicon are well developed. They are a very promising class of antenna arrays for milli-meter and submillimeter applications. Further development of this technology involves integrating mixers and amplifiers into the antenna arrays. In an effort to develop an antenna-mixer array based on the existing technology, various antenna probes inside the pyramidal horns have been examined on scaled model-horns at the microwave frequencies. In this paper, modeling results and design principles of these antenna probes have been presented, which include the resonant impedance, the operating frequency, and the bandwidth of the horn antennas. These measurement results provide a guideline in designing probes for millimeter/submillimeter-wave integrated-circuit horn-antenna-mixer arrays.**

I. Introduction

In millimeter/submillimeter-wave systems, because of their shorter wavelengths compared with microwave systems, the waveguide circuits become much smaller, which makes them very difficult and expensive to build. However, quasi-optical components provide a solution to this problem. Millimeter-wave integrated-circuit horn-antennas combine antennas and mixer circuits into a single entity. The design is based on an exiting technology by which dipole excited integrated-circuit horn antennas are made in silicon [1]. The horn antennas consist of probes suspended on a thin oxynitride membrane inside pyramidal horns which are chemically etched in silicon. The antennas are free of dielectric losses and have plenty of space for electronic interconnections between the probes. The aperture efficiency of these etched horn antennas has been improved to 72 % [2]. Recent research shows that the experimental results agree well with the theoretical analysis, including radiation patterns and resonant dipole impedances [3]. These types of circuits could be mass produced by standard integrated-circuit technology and will find applications in millimeter-wave imaging systems, remote-sensing, radio astronomy, and communication systems.

The horn-antenna-mixer design requires consideration of the impedance matching, conversion loss and frequency response of the antenna-mixer circuit. Antenna probes are required not only to couple the free-space wave energy to the mixer circuit but also to provide a suitable impedance, the embedding impedance, to the mixer diodes. This impedance over a wide frequency range is also important for mixer performance because various frequency components exist in the mixer circuits. In order to achieve

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an impedance-matched antenna-mixer array, the characteristics of the antenna probes inside the horns must be investigated.

II. Probe Modeling

The impedances of various probes were measured in low-frequency model-horns, which were made of two different types. One type was a 3×3 array made of aluminum, and the other type was a half horn made of copper sheet sitting on a big copper-clad circuit board that was used as an image plane. The half horn on a ground plane was used in order to eliminate difficulties in modeling the transmission line normally used to feed the dipole in a full horn. These two types of modeled horns were used alternatively, depending on the feed location of the probe inside the horn. The modeled design frequency is 5 GHz. The horn opening is $1\,\lambda$, and the probe is placed inside the horn about $0.37\,\lambda$ away from the apex. The probe element was soldered to an SMA bulkhead feed-through, which was in turn soldered to the copper surface of the image plane. The thickness of the copper sheet being used to make probes is about 0.13 mm and the width of the probe is about 1.0 mm except for the fan-probe. Measurements were made using an HP 8510 Network Analyzer, which was calibrated to the end of the test-set cable using coax standards. The electrical-delay feature was used to effectively remove the line between the test-set cable and the probes. The probe configurations are shown in Figure 1 and the measured probe impedance plotted on the Smith chart are illustrated in Figure 2.

Frequency Tuning — Figure 1(a) shows a monopole in a full horn. On the Smith chart (Figure 2(a)), the impedance is plotted as a function of the monopole length. The resonant resistance of $16\,\Omega$ is achieved at the monopole length of $0.22\,\lambda$. In comparison,

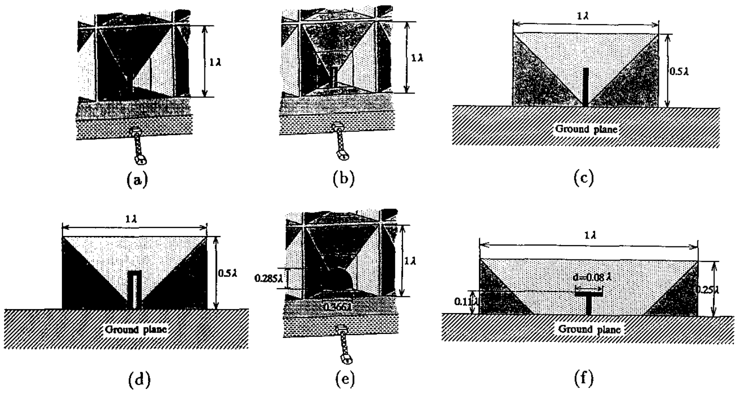

Figure 1 Probes inside pyramidal horns; (a) monopole, (b) folded-monopole, (c) half dipole, (d) half folded-dipole, (e) fan-probe, (f) half loaded-dipole inside a rectangular horn.

the resonant resistance of a lossless monopole on a ground plane in free space is 25 Ω for a monopole length of 0.25 λ. Figure 1(c) shows a half dipole in a half horn. The impedance is plotted as a function of the half-dipole length (Figure 2(c)). The resonant resistance is 25 Ω at the half-dipole length of 0.20 λ. Since the voltage across the half dipole in the half horn is half that in a full horn, the measured impedances are only *half* of the actual impedances; therefore, for a dipole in a full horn, the resonant resistance is 50 Ω at the full-dipole length of 0.40 λ. This result was verified by millimeter-wave measurements [2] and theory [3]. This dipole probe also provides a very good matching impedance for the mixer diode pair. In comparison, the resonant resistance of lossless dipole in free space is about 50 Ω at the dipole length of 0.50 λ.

Impedance Tuning — Figure 1(b) shows a folded monopole in a full horn, with one leg attached to the coax-center-conductor and the other leg grounded to the horn sidewall. The impedance is plotted as a function of the monopole-probe length (Figure 2(b)). A resonant resistance of 50 Ω is obtained for a monopole length of 0.19 λ. This resistance matches the impedance of two mixer diodes connected in antiparallel. Hence, this folded monopole is suitable for LO reception in a fundamentally-pumped antenna-mixer-array. In free space, however, the resonant resistance of a lossless folded monopole on a ground plane is about 100 Ω at the folded-monopole-probe length of 0.25 λ. Figure 1(d) shows a half folded-dipole in a half horn. The impedance is plotted as a function of the half-dipole length (Figure 2(d)). The resonant resistance of 68 Ω is obtained at the half-dipole-probe length of 0.18 λ. For the same reason stated above, the resonant resistance of a full folded-dipole in a full horn would be 136 Ω at the full-folded-dipole length of 0.36 λ, compared with 200 Ω for a lossless folded dipole in

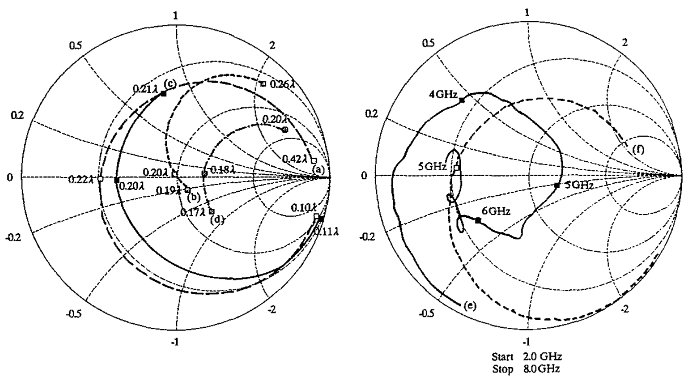

Figure 2 The probe impedance plotted on the Smith chart. (a) monopole, (b) folded-monopole, (c) half dipole, (d) half folded-dipole, (e) fan-probe, (f) half loaded-dipole inside a rectangular horn.

the free space. This folded-dipole impedance needs to be transformed to be about $200\,\Omega$ to be used as an RF reception element in a balanced fundamentally-pumped antenna-mixer-array design.

Broad Bandwidth — Figure 1(e) shows a fan-probe in a full horn, which is designed as a broadband probe-excited horn-antenna. By tuning the flare angle and width of the fan, a resonant resistance of $65\,\Omega$ has been obtained at the design frequency of 5 GHz. The return loss is better than 10 dB over a frequency range of 2 GHz. Figure 2(e) shows the impedance plotted as a function of frequency.

Probe Loading — Figure 1(f) shows a half loaded-dipole in a half rectangular-horn, to be used potentially for LO reception in the subharmonically-pumped antenna-mixer. The dipole probe was loaded with a short stub on the end near the horn sidewall to compensate for the capacitive impedance of the relatively shorter dipole-probe. Figure 2(f) shows the impedance plotted as a function of frequency. The resonant resistance of $18\,\Omega$ is achieved at the loading-stub length of $0.08\,\lambda$, which corresponds to $36\,\Omega$ for a full loaded-dipole in a full horn. This loaded-dipole can be used to match the impedance of two mixer diodes connected in antiparallel. A half loaded-folded-dipole in a half rectangular-horn was also tested. The resonant resistance of $54\,\Omega$, or $108\,\Omega$ for a full loaded-folded-dipole, was obtained at the loading-stub length of $0.12\,\lambda$. This probe could provide a suitable matching impedance for single-diode mixers.

III. Conclusion

All these impedance measurements indicate that the presence of the horn increases the effective length of the probe element, which agreed well with the millimeter-wave aperture efficiency measurements [2] and the theoretical analysis [3], in which a dipole probe was used as an antenna element. They also indicate that the resonant frequencies can be controlled by changing the length of the probes or loading the probes, and that resonant resistances can be increased to a reasonable matching range by folding the probes. The fan-probe design indicates that the bandwidth can be increased by changing the probe width. These modeling measurements illustrate the probe design principles in an extended frequency range and provide very useful options in choosing probe elements in integrated-circuit horn-antenna-mixer arrays.

IV. Acknowledgements

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V. References

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