QUASI-OPTICAL ANTENNA-MIXER-ARRAY DESIGN FOR TERAHERTZ FREQUENCIES

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ABSTRACT

A new quasi-optical antenna-mixer-array design for terahertz frequencies is presented in this paper. In the design, antenna and mixer are combined into an entity, based on the technology in which millimeter-wave horn antenna arrays have been fabricated in silicon wafers. It consists of a set of forward- and backward-looking horns made with a set of silicon wafers. The front side is used to receive incoming signal, and the back side is used to feed local oscillator signal. Intermediate frequency is led out from the side of the array. Signal received by the horn array is picked up by antenna probes suspended on thin silicon-oxynitride membranes inside the horns. Mixer diodes will be located on the membranes inside the horns. Modeling of such an antenna-mixer-array design is done on a scaled model at microwave frequencies. The impedance matching, RF and LO isolation, and patterns of the array have been tested and analyzed.

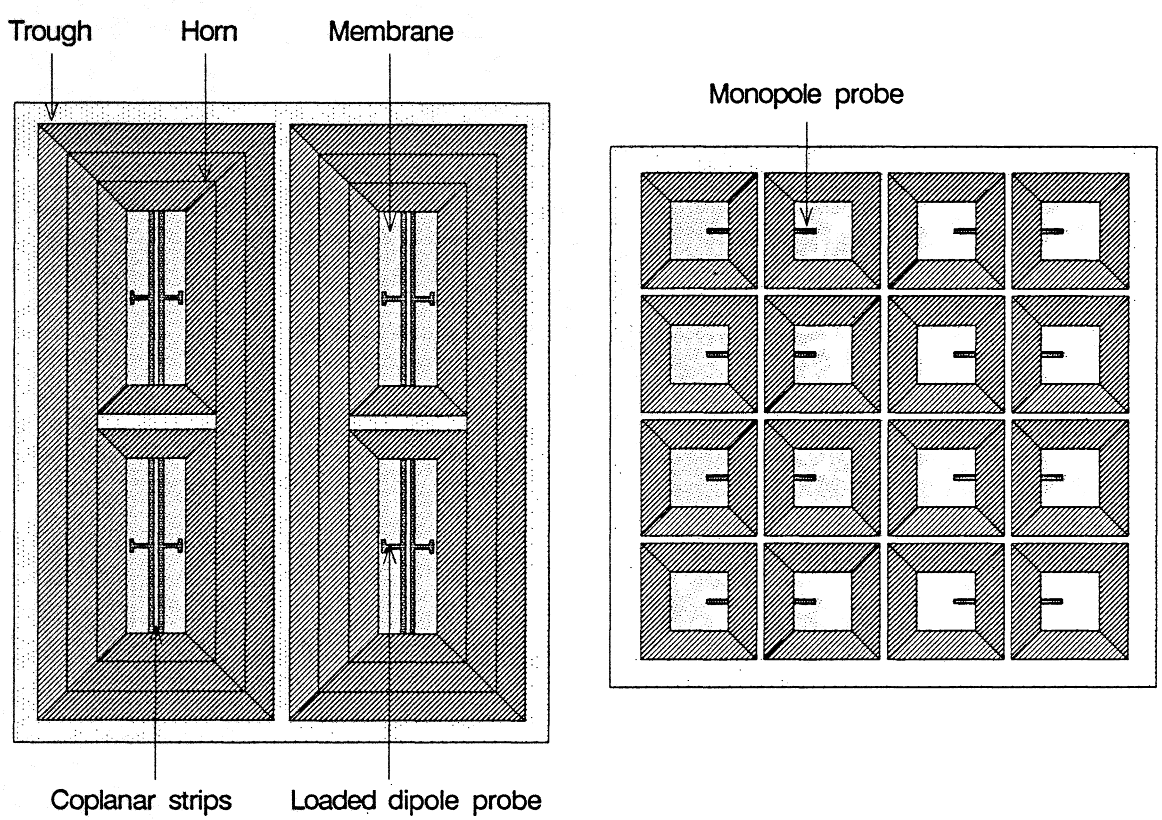
I. INTRODUCTION

In submillimeter-wave and terahertz frequency systems, because of their much shorter wavelengths compared with microwave systems, waveguide circuits become much smaller, which makes them very difficult and expensive to build. However, quasi-optical components provide a solution to this problem. Quasi-optical antenna-mixer-array combines antennas and mixer circuits into a single entity. The design is based on an existing 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]. Various antenna probes inside the pyramidal horns have also been studied [4].

This integration of antenna and mixer eliminates the need for RF and LO circuit-fashion connections. Such construction offers a device with potential of smaller size, lighter weight, more ruggedness and less cost, as compared to conventional methods. Moreover, this kind of design potentially can be mass produced by standard integrated-circuit technology. The applications of the integrated-circuit antenna-mixer array include imaging systems, radars, and satellite communications.

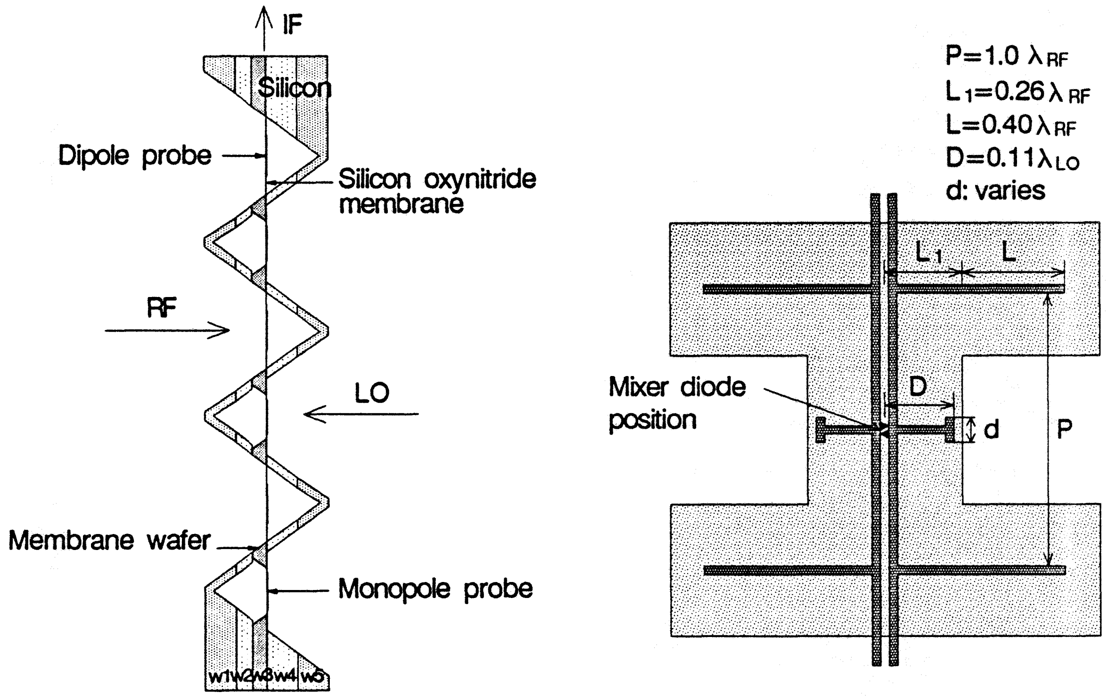
II. Horn Structure and Mixer Circuitry Design

In order to avoid the difficulty to supply an LO power at a frequency close to RF, a subharmonically-pumped antenna-mixer array is designed which is pumped by an LO at only half of the RF frequency. Since the RF and the LO frequencies differ by approximately a factor of two, in principle, it is easier to realize the isolation between the RF and the LO. Furthermore, spurious responses associated with the odd harmonics of the LO can be rejected by using an antiparallel diode pair. The subharmonically-pumped horn-antenna-mixer array is shown in Figures 1 and 2. It consists of a set of forward- and backward-looking horns facing back to each other made silicon wafers. Every four RF horns are provided with one LO horn which is a rectangular-shaped horn. The spacing between RF horns is 1λ. By using the sub-array concept, every four RF horns can be taken as a sub-array. Four RF horns, together



(a) (b)

Figure 1 The horn structure of the subharmonically-pumped mixer design, one LO horn corresponding to four RF horns; (a) LO horns, the trough made of two silicon wafers is put on the top of the horns. (b) RF horns, monopoles are used for the RF reception.



(a) (b)

Figure 2 (a) Cross-sectional view of the antenna-mixer array. (b) The mixer circuit design for a unit cell; four monopoles for the RF reception and one dipole for the LO reception; both RF and LO are detected by the mixer diodes located in the center of the unit cell; IF is led out from the ends of the LO horn through a coplanar-strip transmission line.

with one LO horn, form a unit cell. This design will keep the best symmetry, and the beam patterns of the sub-array will be improved by a factor of 4 compared with that of the single RF horn. Since the size of the LO horns should be twice that of the RF horns, half of the area on the LO side in each unit cell would be left unused. This would cause strong reflection from the flat surface, namely, a 3 dB reflection loss. In order to eliminate this 3 dB reflection loss, a structure is designed to be placed on the top of the LO horns. The structure has a long trough on each row of the LO horns and will fill up the space between the LO horns to converge the incoming energy into the LO horns. Figure 1 shows the antenna-mixer array with 2×2 LO horns looking from the LO side and 4×4 RF horns looking from the RF side. The cross-sectional view is shown in Figure 2(a). The mixer circuit design is shown in Figure 2(b). Every monopole from each of the four RF horns will couple the RF signal down to the LO horn through a coplanar-strip transmission line. A dipole probe is employed to receive the LO. The mixer diodes are located in the center of the LO membrane, and the IF is led out from the ends of the LO horn. The dipole probe is loaded on the ends near the sidewalls with a short stub, which, as a result, could compensate for the capacitive characteristic impedance of the short dipole probe.

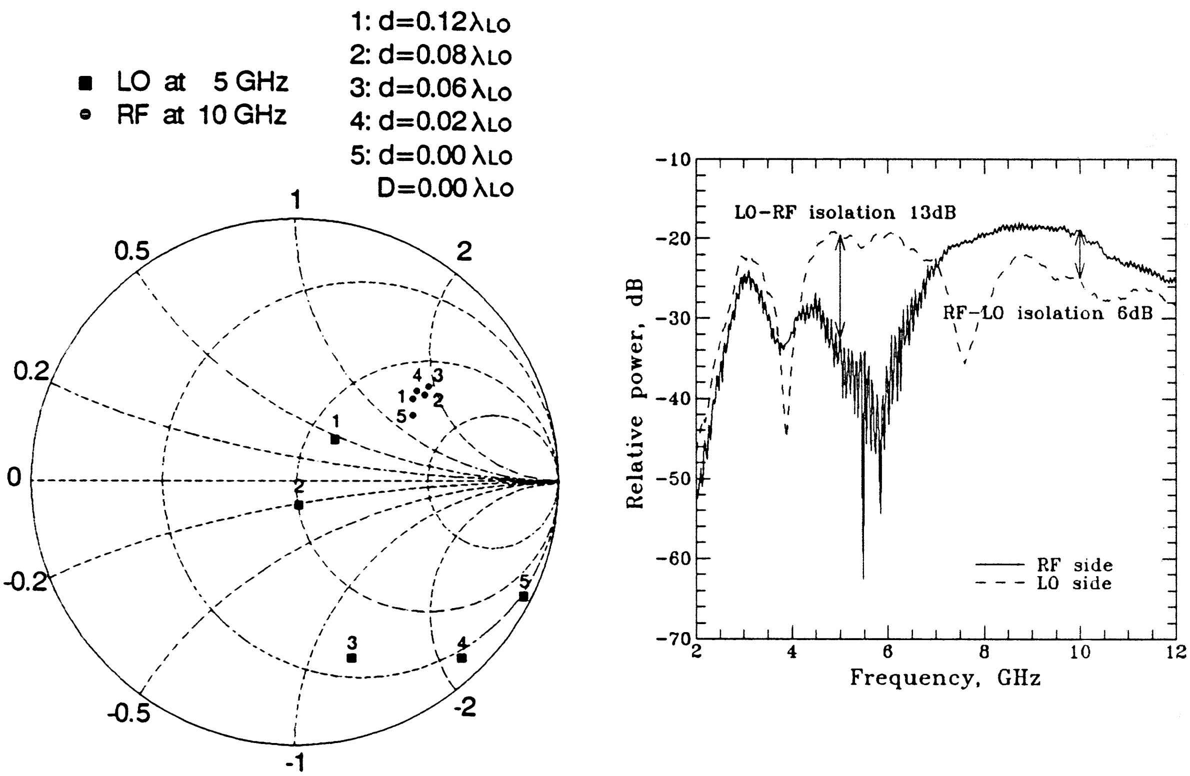
III. Modeling

The mixer array design has been tested on a scaled model sub-array, which has four RF horns and one LO horn. The gain of such a sub-array will be increased by a factor of 4 compared with a single horn. Based on this scaled model sub-array, antenna impedances and receiving patterns were measured. 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 good isolation between the RF and the LO, as well as to match the impedances of the RF and the LO to the diode impedance, various mixer circuits have been tested. Trade-off has been made among the impedance match and the isolation between the RF and the LO so as to minimize losses.

The actual model consists of two square RF horns and a half rectangular LO horn, a half of the designed unit-cell, sitting on a big copper-clad circuit board which was used as an image plane. The monopole built in each of the RF horns will couple the incoming signals to the loaded dipole in the LO horn through the coplanar-strip transmission line. A small channel in the middle of the horns will let the monopole probes go through between the LO and RF horns. The design frequency for the RF is 10 GHz and the LO is 5 GHz, corresponding to the wavelength of 3 cm and 6 cm, respectively. The opening of RF horns is $1\,\lambda_{RF}$ square, while the height of the LO horn is $\lambda_{LO}/2$, and the LO horn width is $1\,\lambda_{LO}$. Mixer diodes are to be placed in the center of the dipole probe in the LO horn. An SMA bulkhead feed-through connector is soldered from the back of the circuit board to the place where the diodes are supposed to be. The inner conductor of the connector is soldered to the dipole probe, and the outside conductor is soldered to the circuit board used as a ground plane.

Measurements were done on an HP 8510 Network Analyzer and data were collected by a PC. Full two-port calibration was made in order to measure not only the reflection coefficients but also the receiving properties and the isolation between the RF port and LO port by measuring the transmission coefficient S_{12}. For this purpose, a broadband horn antenna is used as a transmitting horn which has a working frequency range from 2 GHz to 18 GHz. The measured impedances are marked on the Smith chart in Figure 3(a). Although the impedances were measured on only a half unit-cell, consisting of two RF horns and a half LO horn, the impedances in a full unit-cell can be easily obtained by doubling those measured impedances in the half unit-cell. The impedances in Figure 3(a) are plotted by using Puff, a software CAD program [5]. Both the RF and the LO impedance should be matched to $50\,\Omega$ because each beam-lead diode in the antiparallel diode pair has a resistance of about $100\,\Omega$. In the graph, when the loading stub on the dipole decreases in length, the LO impedance at 5 GHz changes from the inductive to the capacitive impedance, passing the resonant resistance at about $50\,\Omega$, which is a very good matching impedance for the diode pair. This LO impedance of the circuit can be regarded as the LO dipole-probe impedance parallel with the impedance of the coplanar transmission line plus the RF probes. At 5 GHz, the impedance of the coplanar transmission line plus the RF probes is very high as is illustrated by the LO frequency mark "5" when the entire LO dipole probe is taken away. Hence, the resonant LO impedance is mainly determined by the loaded dipole probe and is relatively independent of rest of the circuits. On the other hand, the RF impedances at 10 GHz are pretty high and independent of the loading-stub length changes. The average value of those RF impedances at 10 GHz is about $84 + j82\,\Omega$.

The normal-incident power receptions by the RF and the LO horns were tested over a wide frequency range, from 2.0 GHz to 12.0 GHz. This was done by putting a wide-band transmitting horn in front side of the RF horns or the LO horn. Figure 3(b) shows the measured power received by the RF horns when the transmitting horn is on that side (solid line) and by the LO horn when the transmitting horn is that side (dashed line). At the LO frequency of 5 GHz, the difference between the LO and the RF power is defined as the LO-RF isolation. The higher isolation, the lower the coupling loss, under the condition that other parameters stay the same. Similarly, the RF-LO isolation is the power difference between RF and LO at the RF frequency



(a) (b)

Figure 3 (a) The circuit impedances is indicated on the Smith chart with respect to the different loading-stub length d; measured at 10 GHz for the RF and 5 GHz for the LO. (b) Measured normal-incident power, received by the RF horns (solid line) and by the LO horn (dashed line) with equal distance.

Loss component	Simple-probe design	Split-LO-probe design
RF mismatch, dB	1.7	4.9
LO mismatch, dB	0.0	0.2
RF-LO coupling, dB	1.3	0.0
LO-RF coupling, dB	0.2	0.2

Figure 4 Comparison of the impedance-mismatch losses and the coupling losses between the two different mixer circuit designs.

of 10 GHz. The measured RF-LO isolation is 6 dB or a 25 % loss. If the LO probe is split into two, by tuning the spacing between two LO probes, minimum RF-LO isolation of 20 dB was achieved. As a comparison, of the simple-probe design and the split-LO-probe design, the impedance-mismatch losses and the coupling losses of the two designs are listed in the table in Figure 4. For both designs, the biggest loss comes from the RF-impedance mismatch, 1.7 dB for the simple probe and 4.9 dB for the split-LO-probe.

IV. Conclusion

A new antenna-mixer array design has been presented, which potentially can be made and used at submillimeter and terahertz frequencies. Modeling work shows that, for this design, compromises have to be made between the RF-impedance mismatch, the LO-impedance mismatch and the RF-LO coupling losses. In some applications, if certain LO loss is tolerable, then lower RF loss can be achieved (which means lower conversion loss) by sacrificing some LO impedance-mismatch losses and LO-RF coupling losses. The mixer elements could be either Schottky diodes [6] or superconducting SIS mixers [7].

V. Acknowledgements

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VI. References

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