obtained in Fig. 4, with different tuning stub lengths L_t for a given cap angle α.

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An Integrated LTCC Millimeter-Wave Planar Array Antenna With Low-Loss Feeding Network

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***Abstract*—A novel configuration of millimeter-wave planar array antenna based on low-temperature cofired ceramic (LTCC) technology is investigated. The configuration exploits the three-dimensional (3-D) integration feature of LTCC by incorporating a novel quasi-cavity-backed patch (QCBP) element using a pair of grid-like conductor walls and a mixed feeding network configuration. A proposed LTCC planar array antenna consisting of 16 by 16 elements is designed, manufactured and tested. Good agreement is achieved between the theoretical performance and the measured results.**

***Index Terms*—Array antenna, laminated waveguide, low-temperature cofired ceramic (LTCC), patch antenna.**

I. Introduction

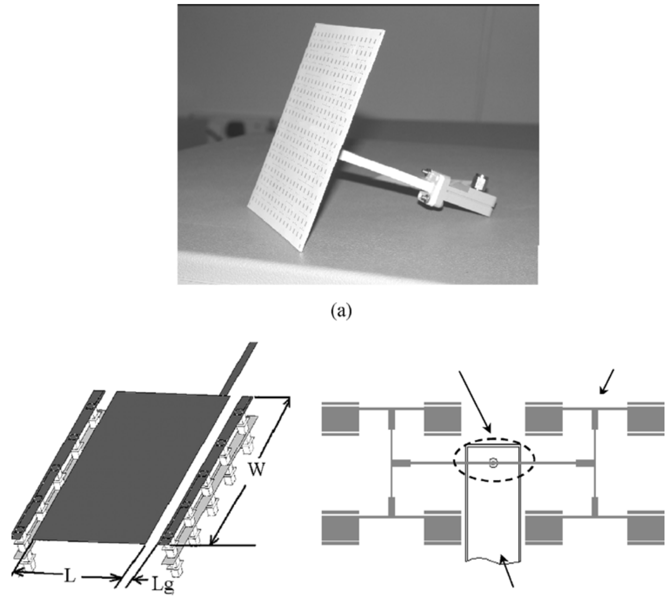

Fig. 1. (a) Photograph of the integrated LTCC array antenna. (b) Perspective view of the QCBP element (bottom ground plane is not shown). (c) Layout of the 2 by 2 subarray and the mixed feeding scheme.

With the increasing demands of commercial millimeter-wave applications such as collision avoidance radar and local multipoint distribution systems (LMDS), a multilayered low-temperature cofired ceramic (LTCC) large-scale array antenna has attracted some attention due to its flexibility in manufacturing, the capability of passive integration and the low production cost. One potential application is to build a microstrip array antenna in LTCC substrate. However, operating at millimeter-wave frequencies, a conventional microstrip patch array antenna on LTCC substrate would be less attractive because of its low element radiation efficiency and the loss from feeding network, which are caused by the relatively high dielectric constant of the LTCC substrate.

In this communication, a 256-element array antenna operating at 29 GHz on a 12-layer $12.7 \times 12.7\ \mathrm{cm}^2$ LTCC tile is designed and manufactured. Fig. 1(a) shows a photo of the array antenna, which is directly fed by a piece of WR28 waveguide on the backside. A quasi-cavity-backed patch (QCBP) antenna is used as radiating element as shown in Fig. 1(b). It will be shown that the QCBP antenna can achieve a better radiation performance than that of its counterpart without the cavity. To reduce the loss and unwanted radiation from the feeding network, a mixed feeding network configuration comprising laminated waveguide (LWG) [1], microstrip line and required transitions is proposed. The novel LTCC array antenna has been designed and measured. Good agreement between simulated and measured results is obtained.

II. Radiating Element

It is known that the bandwidth of a traditional patch antenna is proportional to the substrate thickness. To achieve a wider bandwidth, a thicker substrate can be used. However, working with the high dielectric constant substrate, a thicker substrate will lead to a higher surface wave loss and consequently degrade the radiation efficiency. For example, an antenna built on Dupont 943 LTCC substrate (with dielectric constant of 7.5, a loss tangent of 0.002, and a thickness of 0.447 mm) that is capable of achieving a 4% 2:1 VSWR bandwidth at a center frequency of 29 GHz, has a computed radiation efficiency of less than 78%. To improve the radiation efficiency, a QCBP antenna is introduced, as shown in Fig. 1(b). The length of radiation edge and non-radiation edge are denoted as W and L, respectively. Two grounded grid-like conductor walls, comprising several metal strips and filled via

Manuscript received November 27, 2003; revised August 23, 2004. This work was supported in part by the Research Grants Council of the Hong Kong Special Administrative Region under Grants 2150279, CUHK 4202/01E and in part by the Natural Science Foundation of China under Project Contract 60171017.

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Digital Object Identifier 10.1109/TAP.2004.842588

TABLE I
SIMULATED RADIATION EFFICIENCY OF THE SUBARRAY

Lg (mm)	D (dB)	η (%)	W (mm)	L (mm)
0.127	13.1	94.6	2.49	1.49
0.152	13.1	92.3	2.49	1.52
0.178	13.1	90.4	2.49	1.55
Traditional Patch	13.0	77.9	2.54	1.57

holes, are introduced to minimize the excitation of surface waves and thus improve the radiation efficiency.

A numerical analysis has been conducted to study the radiation performance of a 2 by 2 subarray, as depicted in Fig. 1(c), with the proposed antenna element using the IE3D EM simulation software. As shown in Table I, by using the grid-like conductor walls the radiation efficiency of the subarray (η) can be as high as 94.6% as compared with an efficiency of 77.9% for the case without the walls. The separation distance of the wall to the edge of patch antenna L_g should be kept close to the extension length of the fringe field of the patch to maximize the radiation efficiency. Due to the leaking effect of the meshed wall structure, as shown in Table I, the simulated optimal L_g is found to be 0.127 mm, which is less than the theoretical extension length of 0.178 mm.

III. MIXED FEEDING NETWORK

Owing to the feature of no radiation loss and low insertion loss, a laminated waveguide (LWG) is considered as one of the most effective transmission lines for LTCC millimeter-wave applications. A three-dimensional (3-D) laminated waveguide is built by depositing metal planes on top and bottom surfaces of a multilayered substrate and using a pair of grid-like conductive walls as sidewalls [2]. Assuming low loss and no leakage for the LWG, a mixed feeding network is proposed as shown in Fig. 2. The main trunk of the feeding network is constructed by the LWGs. Since extending the LWG feeding network to each elements in the array antenna significantly increases the complication with negligible loss reduction, as illustrated in Fig. 2, the subfeeding network of all the 2 by 2 subarrays utilize traditional microstrip lines. The laminated waveguide feeding network and the 2 by 2 subarrays are separated by an internal ground plane, which serves as the bottom ground plane of the array and the top metal wall of the LWG feeding network, as shown in Fig. 3. A laminated waveguide to microstrip line T-junction [3], described by the authors, can be used to connect the laminated waveguide feeding network to the microstrip line feeding network. To provide the LTCC array with an interface to an air waveguide system, a broadband transition between a laminated waveguide, and a WR28 standard waveguide (LWG-to-WG transition) [4] has been developed and is integrated in the feeding network.

IV. LOSS ANALYSIS AND EXPERIMENTAL RESULTS

A prototype of the patch antenna array with the quasi-cavity-backed elements and a prototype of the same patch antenna array without cavity-backing were fabricated using a 12-layer substrate of Dupont 943 Green Tape. An identical feeding network structure is used in both prototypes. In the 12-layer substrate, the LWG feeding network is built in the lower eight layers and the antenna elements and microstrip line feeding network is built in the upper four layers, as shown in Fig. 3. The thickness of each layer is 0.11 mm. The 16 by 16 elements in the array antenna are excited equally. To prove the concept of the mixed feeding network and also save the real estate for other loaded LWG components, only the first branch of the main trunk is implemented by LWG in the experimental array. The two types of required transitions, namely the transition from air waveguide to LWG and the T-junction

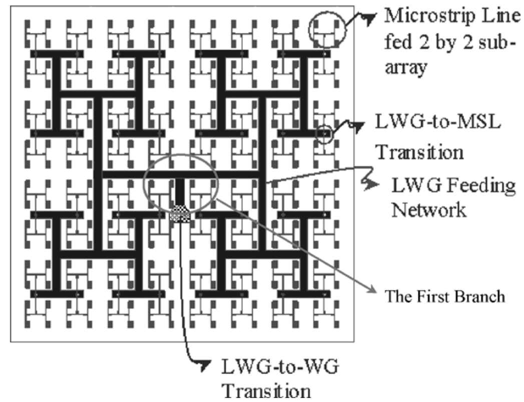

Fig. 2. Proposed mixed feeding network configuration.

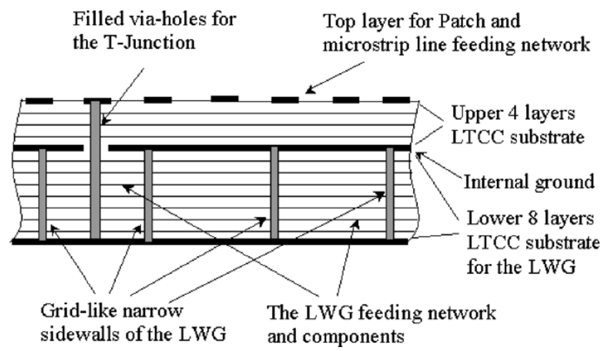

Fig. 3. Vertical structure of the feeding network.

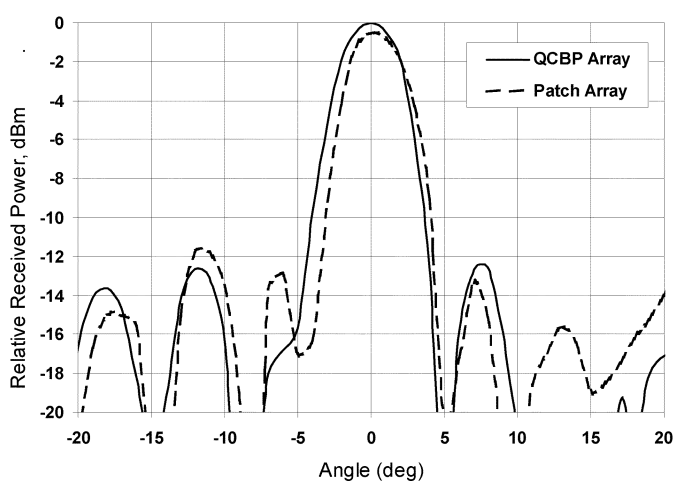

Fig. 4. Measured E-plane radiation patterns of the array using patch elements and the QCBP elements.

from LWG to microstrip line, have been integrated in the experimental feeding network.

Simulated results obtained from ANSOFT HFSS at the operating frequency of 29 GHz show that the insertion loss of the proposed mixed feeding network, and a traditional microstrip edge feeding network are 3.7 and 9.6 dB, respectively. The cross-sectional dimension of the LWG is 2.5 mm by 0.22 mm and the microstrip trace width of the 100-ohm microstrip line used in the microstrip line feeding network is 0.1 mm. The simulated insertion loss of the experimental feeding network is 6.6 dB. Although the experimental feeding network is just a portion of the proposed mixed feeding network, the improvement over the microstrip line feeding network is significant enough to verify the mixed feeding network concept. Based on the calculated radiation efficiency presented in Table I, it can be concluded by simulation that the gain of a QCBP array with mixed feeding network and a conventional element array with a microstrip line feeding network is about 26.5 and 20.4 dBi, respectively. Even for the experimental array, in which LWG is used only for the first branch of the feeding network and the quasi-cavity-backed elements are used, about a 24.2 dBi gain can be achieved.

Fig. 4 shows the measured E-plane radiation pattern of both fabricated array prototypes at 29 GHz. It is observed that the improvement of the measured gain with the quasi-cavity-backed elements over the one without cavity-backed elements is about 0.62 dB, which is slightly less than the theoretical gain difference of 0.84 dB as indicated in Table I. The measured gain for the experimental QCBP array and ordinary patch array is 23.5 and 22.9 dBi, respectively. The difference of about 0.7 dB compared with the simulated result is possibly due to the mismatch of the junctions in the feeding network, which is not included in the loss analysis.

V. CONCLUSION

A novel configuration of integrated LTCC array antenna working in the millimeter-wave frequency band has been proposed by exploiting the flexibility of LTCC technology for 3-D integration. The antenna array uses QCBP as radiating elements. This configuration could be used in various integrated millimeter-wave antenna modules. To reduce the loss from the feeding network, a mixed feeding network configuration is proposed and verified by experiment. This communication concludes that with the LTCC multilayer technology a large scale and high gain array antenna can be built and integrated with other millimeter-wave functional components in the same ceramic tile.

ACKNOWLEDGMENT

The authors would like to thank the reviewers for their constructive comments and suggestions. Special thanks go to the Editors for their iterative efforts in polishing the manuscript.

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Parameterization of the Tapered Incident Wave for Numerical Simulation of Electromagnetic Scattering From Rough Surface

Hongxia Ye and Ya-Qiu Jin

***Abstract*—The tapered wave with the tapering parameter g has been applied to numerical simulation of electromagnetic scattering from randomly rough surface with illuminated finite surface length L. This communication presents how to select the parameters g and L, and shows quantitative relationship with the incident angle. The parameter g, as a function of incident angle, should be large enough to make the wave equation in the range of allowable error. The surface length L, larger than several correlation lengths, should be large enough to suppress the punctuated power at the surface edges and be limited to make efficient computation. Combining these criterions, a graphical format to locate g and L for different incident angle θ_i is illustrated. An empirical formula for selecting g and L as a function of θ_i is proposed.**

***Index Terms*—Forward-backward method, numerical simulation, parameterization, rough surface scattering, tapered wave.**

I. INTRODUCTIONS

Numerical simulation of electromagnetic scattering from randomly rough surface has been a topic of successive study for many years because of its broad applications such as terrain remote sensing, radar surveillance over oceanic surface and so on [1], [2]. The Thorsos tapered wave [3] has been extensively applied in order to circumvent artificial reflections from the edges of illuminated finite surface length. Good references can be found in Thorsos [3], Tsang [4], Kapp [5], Toporkov [6], and some others. However, how to determine the parameters of tapered incident wave in numerical computations, such as the tapering waist g, the finite surface length L and their relationship with incident angle, have been remained for further study.

This communication presents a discussion about the selection of the tapering parameters g and L with dependence upon incident angle. The tapering waist g should be large to satisfy the wave equation. The surface length L should be larger than several correlation lengths of the rough surface, minimize the edge effects, and also be limited to make computation efficiency. These requirements locate possible choices of both the parameters g and L with dependence on the incident angle, and an empirical formula for parameters criterions is summarized.

II. HOW TO SELECT g AND L FOR TAPERED INCIDENT WAVE

A two-dimensional (2-D) perfectly electromagnetic conducting (PEC) randomly rough surface is shown in Fig. 1. Random surface height is given by a function $z = \xi(x)$ and its mean height $\langle \xi(x) \rangle = 0$. The matrix equation derived from the discretized MFIE with the MoM process is written as follows [7]

$$\overline{J} = \overline{J}^i + \overline{\overline{P}} \cdot \overline{J} \tag{1}$$

Manuscript received November 28, 2003; revised February 26, 2004. This work was supported in part by the China State Key Basis Research Project 2001CB309401-5 and in part by the China Natural Science Foundation 60171009.

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Digital Object Identifier 10.1109/TAP.2004.842586