Efficient, Low-Cost Integrated Waveguide-Fed Planar Antenna Array for Ku-Band Applications

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***Abstract*—Low-cost printed circuit board waveguide (PCB-WG) technology is employed to develop new waveguide-fed microstrip antenna arrays with low profile and light weight while maintaining high efficiency and gain at 12.5 GHz. The proposed corporate feed network has two parts: on the antenna layer, microstrip lines are used to form a 2 × 4 sequentially rotated subarray of circularly polarized microstrip patches and on the feed layer SIW is utilized to combine any number of these subarrays to form a larger array. Since SIWs transmit the power over a large portion of the feed network, losses are substantially reduced and spurious radiations from feed circuit are eliminated. Several microstrip arrays with PCB-WG feed were designed and fabricated using standard PCB process. Comparing the results with those of a hybrid array with conventional waveguide feed shows that there is only a negligible degradation in gain and efficiency when bulky and expensive aluminum waveguides are replaced by PCB-WGs.**

***Index Terms*—Microstrip antenna array, substrate integrated waveguide, waveguide-fed antenna array.**

I. INTRODUCTION

MICROSTRIP antennas and arrays have found numerous applications in recent years over a wide range of frequencies from UHF up to millimeter waves. This is mainly due to their ease of manufacturing, low cost, compact size, and ease of integration with various planar circuit technologies. However, conventional microstrip feed networks suffer from high ohmic and dielectric losses and introduce significant spurious radiation into the system, both leading to substantial reduction of gain and aperture efficiency of antennas. Therefore, replacing the whole or at least part of the feed network in microstrip arrays with low loss transmission lines have been the subject of intensive research in recent years.

Hollow metallic waveguides can provide the low-loss transmission medium required for the feed network of high efficiency and low-temperature antenna arrays. Replacing the entire feed network of a microstrip array with rectangular waveguides which have to be coupled to individual radiating elements is impractical specially when the side lobes are to be avoided. Therefore, hybrid feed networks in which metallic waveguides combine a number of subarrays of microstrip patches have been investigated [1]–[3]. In [1] longitudinal slots on the broad wall of a rectangular waveguide were used to excite several rows of series-fed linear microstrip arrays. Although this method eliminates the feed loss to a large extent but the resonant nature of the slot coupling narrows the operating bandwidth and spurious radiation from the slots leads to degradation of radiation pattern.

In [3] a highly efficient antenna array for Ku band applications was presented by the current authors. On the top side, subarrays of circularly polarized microstrip patches printed on a very thin FR4 substrate were separated from the ground plane with a slab of foam to enhance their gain and bandwidth. Arrays of 2 × 4 elements were combined with a simple microstrip circuit providing equal magnitude and proper phase in order to further improve the axial ratio. On the back side, a novel and compact corporate feed network composed of rectangular waveguides was designed to combine a number of these subarray modules into a larger array. Instead of slots, a low-loss and wide-band coaxial probe structure was designed to couple each subarray to the waveguide.

Such waveguide feed networks are bulky and severely compromise the low profile nature of microstrip arrays. Furthermore, due to the need for high precision manufacturing, assembly costs, and incompatibility with seamless integration with planar circuits in the receiver front-end, this type of feed structure is not suitable for low-cost, mass producible consumer applications.

The concept of printed circuit board waveguide (PCB-WG) enables printed circuit technology to take advantage of the low-loss transmission in rectangular waveguides within the PCB substrate. In this approach, rows of closely spaced metallic vias between two ground planes emulate the side walls of a thin rectangular waveguide. If the vias are close enough compared to the wavelength, the wave is trapped between the two side walls and propagates along the structure with negligible leakage. Thin, dielectric filled PCB-WGs are more lossy than conventional hollow metallic waveguides, however, PCB-WG is still a much better choice compared to other printed circuit transmission lines when lower loss and elimination of unwanted radiation and couplings are important.

PCB-WGs have found many applications in design and manufacturing of various microwave and millimeter-wave devices in recent years [4]–[6]. Applications of PCB-WG or post-wall

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waveguide in antenna design has been mainly limited to slot array antennas [7]–[10]. In [8] the so-called *laminated waveguide* was used to design and manufacture a circularly polarized slot array antenna at 60 GHz. The laminated waveguide reduces the leakage at junctions and bends where TM-like modes are excited [11]. In [12] a simple 2 × 4 element linear polarized microstrip array was excited through a laminated waveguide. A fairly complex multi-layer transition from the laminated waveguide to microstrip line was designed to couple the top layer to the waveguide feed.

In this letter, PCB integrated waveguides combined with high-gain microstrip array modules are used to develop thin and highly efficient waveguide-fed array antennas with circular polarization at Ku band. A number of small microstrip subarrays are combined using a PCB-WG based corporate feed network to create larger arrays without considerable compromise of the aperture efficiency. This modularity is particularly appealing in commercial mass production of antenna arrays for consumer DBS applications. Using exactly the same subarray modules that were presented in [3] enables us to evaluate the degradation of gain and efficiency of antennas when the bulky and expensive metallic waveguides are replaced with PCB-WGs.

II. MICROSTRIP SUBARRAY MODULES

In this letter, we use the same microstrip antenna subarrays that were designed and tested in [3]. A detailed discussion of the design procedure and simulation results of these subarrays appeared in [3] and will not be repeated here. Each module is printed on a thin FR4 substrate with 0.1 mm thickness. A slab of foam with 1.5 mm thickness separates this printed antenna from the ground plane which is the top plate of the PCB-WG feed structure. The distance between adjacent patches is about $0.8\lambda_0$ at 12.5 GHz. The stubs and notches on each microstrip patch are carefully optimized for highest gain and lowest axial ratio. A circular gain of 9 dBic for each element is achieved while the sequential rotation with quadrature phase shift between adjacent elements leads to an axial ratio of better than 1 dB from 12.2 to 12.7 GHz for each 2 × 2 subarray.

III. PCB-WG FEED STRUCTURE

The corporate waveguide feed structure is composed of H-plane T-junctions, microstrip-to-PCB-WG transitions, and PCB-WG-to-microstrip T-junctions. The first two structures were designed, fabricated, and tested individually before complete design of the PCB-WG-fed array. In this section, we briefly present the design process and simulation results of these components. For measurement purposes, each individual component was connected to coaxial ports using microstrip lines, however, these components are integrated within the array feed structure directly with no microstrip lines between them. Therefore, the simulations were performed in Ansoft HFSS using waveguide ports and no connectors were involved in order to assess the performance of each device in actual environment. The measured results are presented in [13].

IV. COMPLETE PCB-WG-FED ANTENNA ARRAYS

A number of antenna arrays with PCB-WG feed were designed, fabricated and measured and the results are presented in this section. The smallest module which is used as a building block for making larger arrays is a 2 × 4 circularly polarized array shown in Fig. 1 where the PCB-WG-to-microstrip T-junction and microstrip-to-PCB-WG transition on the back plane are also visible. The measured return loss of this antenna is shown in Fig. 2 which is better than 13 dB $(\text{VSWR} < 1.6)$ over a 2-GHz bandwidth. The radiation pattern of this antenna at 12.5 GHz is presented in Fig. 3. Note the slight asymmetry in Fig. 3(a), is due to the configuration of the feeding microstrip lines. Due to excessive computational resources needed by HFSS to simulate the fabricated structure, Agilent Momentum was used to compute the radiation pattern of the 2 × 4 microstrip subarray. In this EM simulator the substrate and ground plane of the array are assumed to be infinite and a lumped voltage source was used for excitation. At broadside, a circular gain of 16.7 dB and axial ratio of 1.67 dB were measured at 12.5 GHz. The EM simulations provide 18.0 dB circular gain and axial ratio of 0.8 dB. The difference is due to (1) the assumption of infinite ground and substrate (2) absence of the input coaxial connector, PCB-WG feed, and PCB-WG-to-microstrip T-junction in Momentum simulations. The measurements were performed using a spinning linear transmitting dipole and the results were adjusted for circular polarization.

As a second example, an array of 2 × 8 elements was fabricated and tested by combining two subarray modules with an H-plane T-junction. The fabricated sample is shown in Fig. 4. The measured return loss and power pattern of this antenna are shown in Fig. 5 and Fig. 6, respectively. Multiple resonances

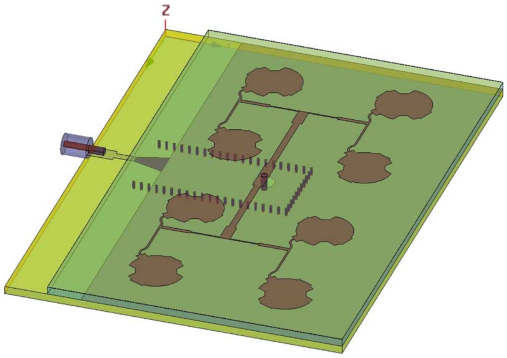


Fig. 1. The 2 × 4 element subarray as stand-alone antenna with PCB-WG feed and coaxial input port.

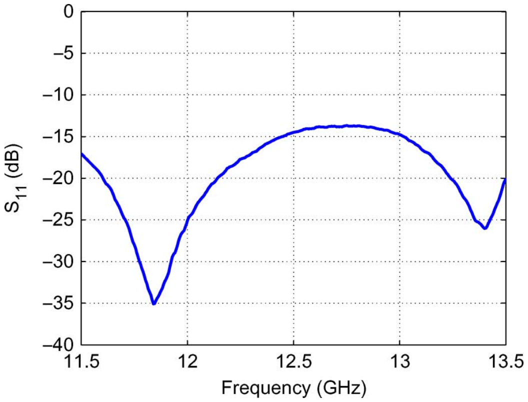
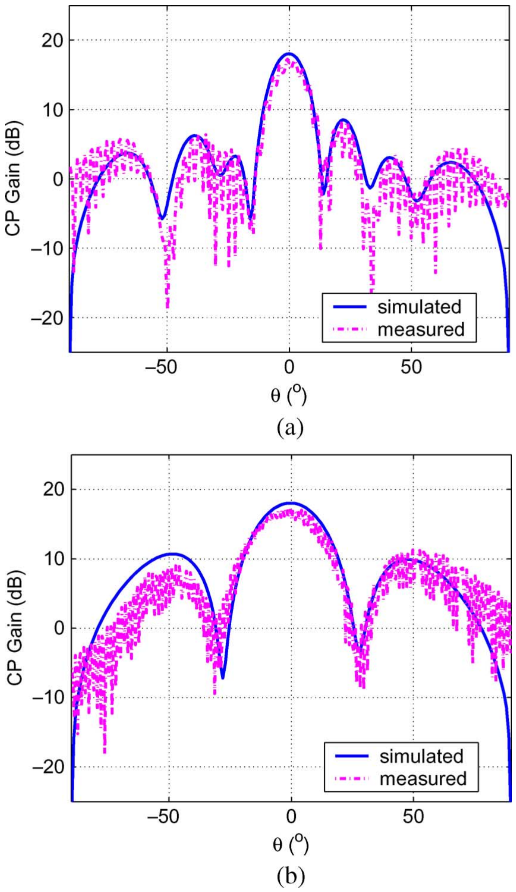


Fig. 2. Measured return loss of the 2 × 4 element PCB-WG-fed array.



(a)

(b)

Fig. 3. Measured versus simulated power gain pattern of the 2 × 4 element array. (a) $\phi = 90°$: the long side of the array; (b) $\phi = 0°$: the short side of the array.

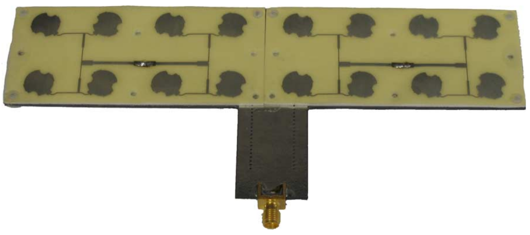


Fig. 4. Top view of fabricated 2 × 8 element PCB-WG-fed array.

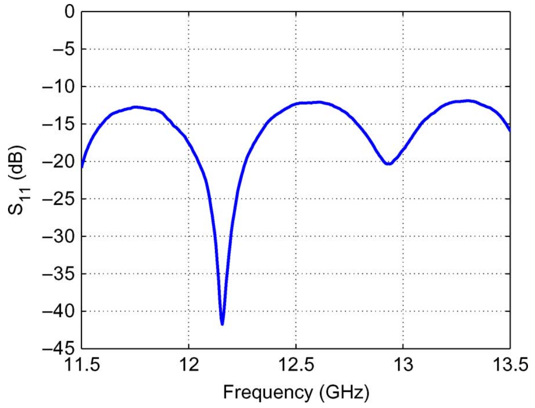


Fig. 5. Measured return loss of the 2 × 8 element PCB-WG-fed array.

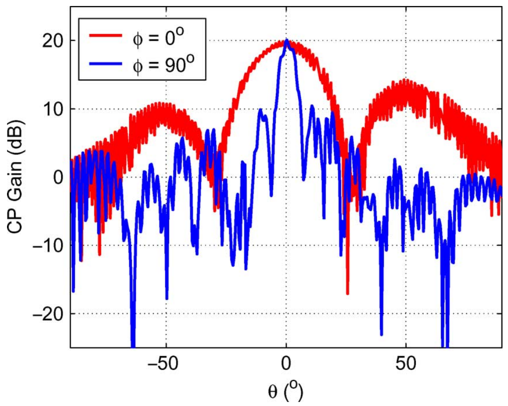


Fig. 6. Measured power pattern of the 2 × 8 element array.

TABLE I
LOSSES FOR THE 2 × 8 ARRAY

Loss type	Metallic (dB)	PCB-WG (dB)
Input connector	0.23	0.23
Microstrip	N/A	0.25
WG transition	0.19	0.18
Antenna subarray	0.14	0.20
Total	0.56	0.86

appeared in the return loss are attributed to the standing wave created within the PCB-WG feed network in which the waveguide arms are shorted at the end. Nevertheless, a VSWR lower than 1.65 has been obtained over a 2-GHz bandwidth. Reflection cancelling posts can be used in order to suppress these resonances which are due to internal reflections in the feed circuit. This issue is under investigation by the authors. The maximum circular polarized gain of this array is measured to be 20 dB with an axial ratio of 1.2 dB at 12.5 GHz. Theoretically, each microstrip patch provides a 9-dB circular gain [3], hence, the ideal value for directivity of this array would be 21 dB, neglecting the coupling between patches and feed loss. Therefore, the radiation efficiency of this array is approximately equal to 79%. The physical size of the array is 183 mm × 40 mm which amounts to an aperture efficiency of almost 60%.

To illustrate the loss differences between regular waveguide for the 2 × 8 array, the various transitions used in the design are independently simulated and the results are presented in Table I.

Finally, an array of 4 × 8 elements was fabricated and measured by combining four subarrays. The fabricated sample is shown in Fig. 7 where the antenna is excited at the back through a coaxial connector. The measured return loss and power pattern of this array are shown in Fig. 8 and Fig. 9, respectively. The maximum circular polarized gain of this array is measured to be 22.5 dB with an axial ratio of 1.8 dB at 12.5 GHz. Theoretical value of the directivity would be 24 dB, neglecting the inter-element couplings and feed losses. Therefore, the radiation efficiency of this array is estimated to be 71%. The physical size

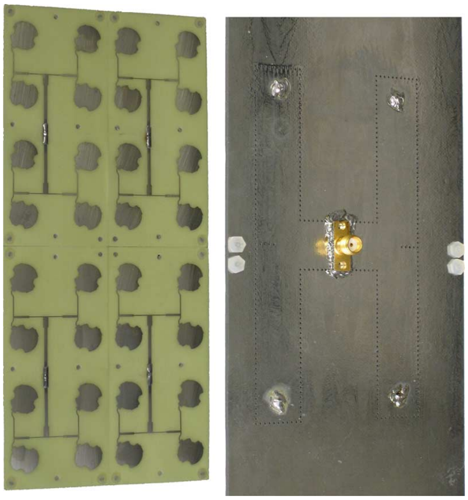


Fig. 7. Front and back sides of 4 × 8 element PCB-WG-fed array.

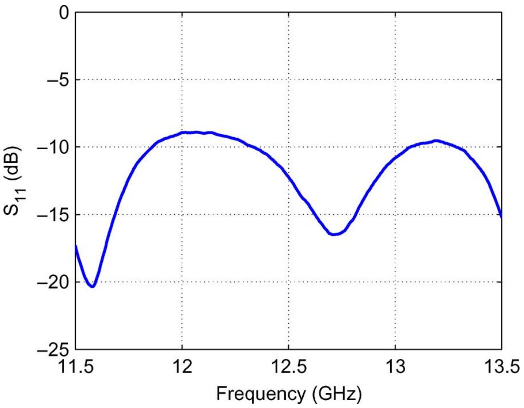


Fig. 8. Measured return loss of the 4 × 8 element array.

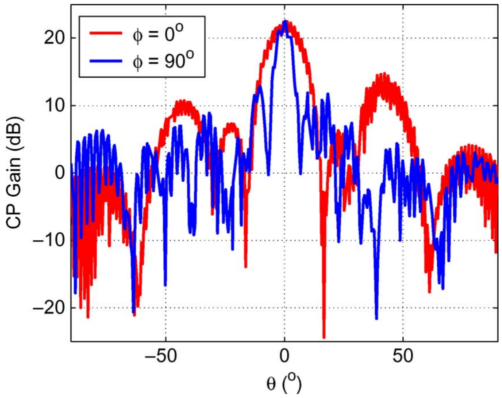


Fig. 9. Measured power pattern of the 4 × 8 element array.

of the antenna is 183 mm × 80 mm resulting an aperture efficiency of almost 56%. Again, multiple resonances in Fig. 8 are due to the internal reflections within shorted waveguides of the feed network.

In [3], a 2 × 16 element hybrid antenna array with a conventional waveguide feed network was presented. That array showed a 23-dB gain and 63% aperture efficiency. Our new 4 × 8 element PCB-WG-fed array shows almost the same gain and has the same physical area. Although these two arrays do not have identical geometries, but the result demonstrates that moving from conventional waveguides to PCB-WG feed network causes only a small degradation in gain and efficiency while the new antennas are light weight, low profile, and easier to integrate with planar circuits. In a mass production scenario, the cost of raw material for conventional waveguide feed can be slightly less than PCB-WG based antenna which needs low loss substrate material instead of aluminium blocks. However, the actual cost of fabrication, which includes high precision milling and assembly costs for hollow waveguides while it only involves simple PCB process for PCB-WG, is at least an order of magnitude higher for the metallic waveguide feed.

V. CONCLUSION

For the first time, substrate integrated waveguide technology was employed to combine high gain circular polarized microstrip subarrays into larger, low profile, and highly efficient antenna arrays at Ku band using a standard PCB manufacturing process. The techniques introduced in this letter can be effectively used at millimeter-waves as well to exploit the benefits of microstrip antennas without compromising the radiation efficiency and without spurious radiations from the feed circuit. Different junctions and transitions between PCB-WG and coaxial ports or microstrip lines were also investigated and a number of antenna arrays with circular polarization were fabricated and tested, demonstrating high efficiency and gain.

REFERENCES

[1] F. Kolak and C. Eswarappa, "A low profile 77 GHz three beam antenna for automotive radar," in *IEEE MTT-S Int. Microw. Symp. Digest*, 2001, vol. 1, pp. 1107–1110.

[2] W. Menzel, M. Schreiner, R. Mack, and P. J. N. Vera, "Millimeter-wave microstrip antenna arrays with waveguide feed network," *Frequenz*, vol. 55, pp. 11–12, 2001.

[3] M. Shahabadi, D. Busuioc, A. Borji, and S. Safavi-Naeini, "Low-cost, high-efficiency quasi-planar array of waveguide-fed circularly polarized microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 53, no. 6, pp. 2036–2043, Jun. 2005.

[4] S. Germain, D. Deslandes, and K. Wu, "Development of substrate integrated waveguide power dividers," *IEEE Canadian Conf. on Elect. and Comput. Eng. (CCECE 2008)*, vol. 3, pp. 1921–1924, May 2003.

[5] W. Che, E. K.-N. Yung, and K. Wu, "Millimeter-wave ferrite phase shifter in substrate integrated waveguide (SIW)," in *Proc. IEEE AP-S Int. Symp. Antennas Propag.*, Jun. 2003, vol. 4, pp. 887–890.

[6] X. Chen, W. Hong, T. J. Cui, Z. Hao, and K. Wu, "Substrate integrated waveguide elliptic filter with transmission line inserted inverter," *Electron. Letts.*, vol. 41, no. 15, pp. 851–852, Jul. 21, 2005.

[7] J. Hirokawa and M. Ando, "Efficiency of 76 GHz post-wall waveguide-fed parallel-plate slot arrays," *IEEE Trans. Antennas Propag.*, vol. 48, no. 11, pp. 1742–1745, Nov. 2000.

[8] H. Uchimura, N. Shino, and K. Miyazato, "Novel circular polarized antenna array substrates for 60 GHz band," in *IEEE MTT-S Int. Microw. Symp. Digest*, 2005, pp. 1875–1878.

[9] L. Yan, W. Hong, G. Hua, J. Chen, K. Wu, and T. J. Cui, "Simulation and experiment on SIW slot array antennas," *IEEE Microw. Wireless Comp. Lett.*, vol. 14, no. 9, pp. 446–448, Sep. 2004.

[10] L. Yan, W. Hong, and K. Wu, "Simulation and experiment on substrate integrated monopulse antenna," in *Proc. IEEE AP-S Int. Symp. Antennas Propag.*, Jul. 2005, vol. 1A, pp. 528–531.

[11] H. Uchimura, T. Takenoshita, and M. Fujii, "Development of a laminated waveguide," *IEEE Trans. Microw. Theory Tech.*, vol. 46, no. 12, pp. 2438–2443, Dec. 1998.

[12] Y. Huang, K.-L. Wu, and M. Ehlert, "An integrated LTCC laminated waveguide-to-microstrip line T-junction," *IEEE Microw. Wireless Comp. Lett.*, vol. 13, no. 8, pp. 338–339, Aug. 2003.

[13] D. Busuioc, "Conformal, integrated antenna array technology for low-cost intelligent system applications," Ph.D. dissertation, Univ. Waterloo, Waterloo, ON, Canada, 2005.