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Broadband single-layer slotted array antenna in SIW technology

D. Mencarelli, A. Morini, F. Prudenzano, G. Venanzoni, F. Bigelli, O. Losito, and M. Farina

***Abstract*—A squint-less slot-antenna array (2D), built on a single substrate integrated waveguides (SIW), is shown. The effort needed for designing a suitable feeding network in SIW technology is justified in view of obtaining lightweight, low profile and low-cost antennas for many applications, including direct broadcast satellite. A proper definition of a "H"-shaped sub-array, made of four slot-pairs, is used to improve the input matching over a wide band. This choice allows remarkable simplification of the fabrication process, as the slots are cut directly in one of the metallic planes forming the SIW.**

***Index Terms*—Substrate Integrated Waveguide (SIW), planar slot-antenna array, Direct Broadcast Satellite (DBS).**

I. Introduction

SUBstrate integrated waveguide (SIW) technology [1] allows the fabrication of rectangular waveguides in dielectric substrates, with the typical advantages of the planar technology, namely cost reduction, low profile, lightness, easy integration of passive and active devices, mass reduction and manufacturing repeatability.

With the above premises, the present design of a SIW planar antenna [2,3] with high gain, squint-less main lobe, and very wide bandwidth (10.7-12.7 GHz), for Direct Broadcast Satellite (DBS) and radar applications, is particularly challenging. In comparison with standard slotted rectangular waveguide (RWG) antenna-arrays [4], or with common satellite dishes, the achievable gain and efficiency are expected to be significantly lower, due to fabrication tolerances and dielectric losses (if inexpensive materials are to be employed) [5-10]. In the literature, many other planar solutions, mostly employing microstrips and patches, have been considered [11-15]. Their performance is typically limited in terms of bandwidth or gain, and a trade-off of these parameters is usually required.

Allocating the entire structure in a single-layer substrate is not an easy task, as crossing of the constituent parts, i.e. feeding network and radiating elements, has to be avoided. The SIWs must be wide enough to operate above cut-off with almost linear dispersion, and the radiating slots should be far away from SIW discontinuities in order to reduce asymmetries. In addition, an inter-element spacing lower than the free-space wavelength is required to avoid the presence of grating lobes.

The achievable gain is limited since antenna-directivity increases linearly with the area of the array, but losses increase exponentially with the length of the feeding network, depending on the loss tangent of the dielectric substrate. The gain obtained in parallel-feeding antennas [16, 17], with double layer configuration, is few dB higher [17] than what obtained by us, at the price of a higher complexity. More importantly, the higher gain is motivated by the use of a substrate with lower dielectric-constant and lower losses: such substrate would be hardly exploitable in a single layer configuration, as we initially carefully verified, due to geometric and spatial constrains.

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II. Antenna Design

The design of the array includes the coaxial-to-SIW transition, the power dividers forming the feeding network, and the terminal radiating elements, represented by 4x2 sub-arrays of radiating slots (Fig. 1).

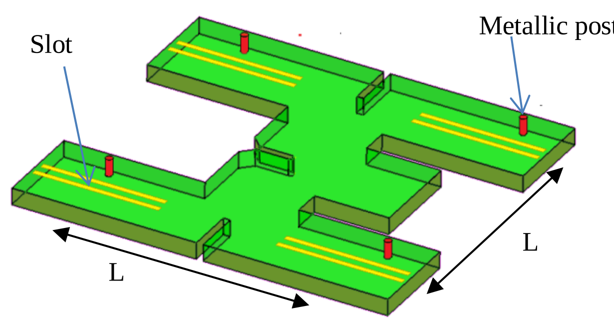


Fig. 1. 4x2 sub-array, in the RWG approximation of the SIW. The spacing between different pair-slots is L=22 mm.

The slots are cut in a copper layer of thickness 35 μm, over a substrate (thickness 1.52 mm) made of Taconic RF-35: this choice constitutes a compromise between cost and losses; the nominal tanδ of the material is 0.0019, with ε_r≈3.5.

In order to obtain good radiation over a large bandwidth, the slots are paired in double-slot sub-systems. We started with a single slot: its resonant length depends on its offset with respect to the SIW center axis, as explained in [4]. The other slot is then placed along the axis of the SIW. The two slots resonate at slightly different frequency: one of them, acting as a "passive" element, is placed along the axis of the waveguide, whereas the second slot, the "active" element, is slightly displaced. They have similar length, but their resonant

frequency changes significantly with the offset from the broad wall centerline [18, 19]. A metallic post, placed near each slot-pair, acts as a reflection element, and enhances radiation.
The largest antenna considered in this work is shown in Fig. 2: it consists of 32x16 radiating slots (area=352x352 mm^2); larger versions are currently being fabricated. The antenna is optimized by tuning slot length and separation, accounting for the inter-element coupling.

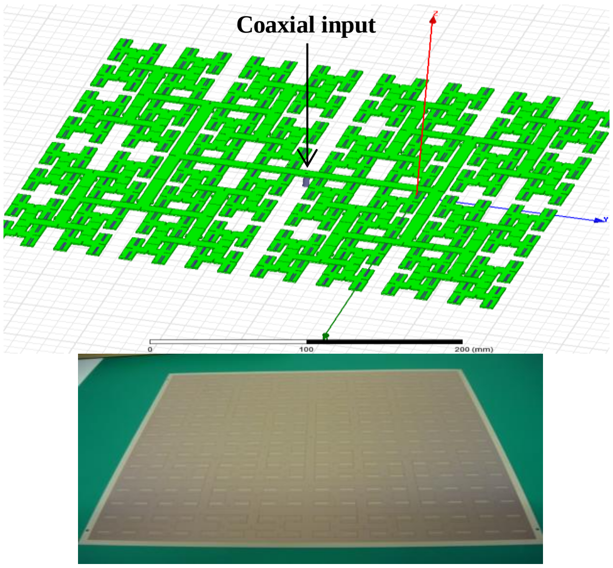


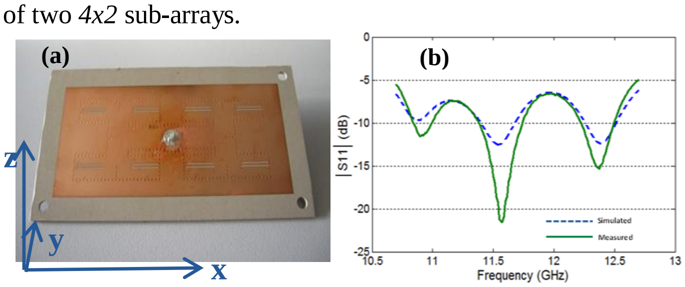
Fig. 2. A view to the [16x32] antenna: layout form the HFSS design project (top) and fabricated device (bottom).

The simulation of such a large antenna is hardly feasible by standard commercial solvers, so that independent simulations of internal and external regions are needed [20]: the former is fed by the coaxial-input and the slots, whereas the latter is given by a half space fed by as many waveguides as the slots. The internal region has been simulated by HFSS, whereas the external region, including slot inter-couplings, is simulated analytically. By definition, internal and external blocks are interfaced through waveguides having the same cross-section as the slots. Some simplifying assumptions are made: i) only one waveguide mode for each slot (field strongly constrained by the geometry), ii) infinite metallic slotted-plane in the external simulation, iii) RWG approximation of the SIW.

III. Experiments

A. *Analysis and measure of an antenna with 4x2 slots.*

As a preliminary example, we report on a SIW antenna made of two *4x2* sub-arrays.



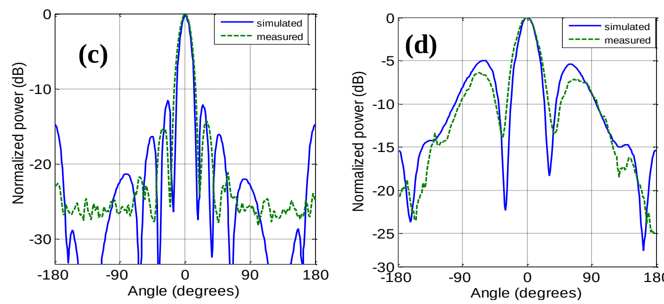


Fig. 3. a) Fabricated SIW antenna, made of two 2 stacked sub-arrays; b) Simulated (blue-dashed) and measured (green-solid) $|S_{11}|$; c) Simulated (solid-blue) and measured (green-dashed) H-plane radiation pattern (11 GHz), d) Simulated (solid-blue) and measured (green-dashed) E-plane radiation pattern (11 GHz).

The device, shown in Fig. 3(a), has been fabricated and tested. Figure 3(b) reports a comparison between simulation and measurement of $|S_{11}|$. For 7 dB return loss, the antenna bandwidth is large, about 20%. The radiation patterns, for both *E*-plane (*yz*) and *H*-plane (*xz*), measured and simulated, are reported in Fig. 3(c) and 3(d).

B. *Analysis of an antenna with 32x16 slots.*

The reflection of the 32x16 antenna (N_{slot}=512), shown in Fig. 2, is reported in Fig. 4: the solid and dashed curves refer to simulated and measured reflections at the coaxial port. The simulation was performed using tanδ=0.003 because, actually, some independent measurements made on uniform SIW waveguides, suggested that tanδ lies in the range [0.0022-0.0038]. The agreement is good, considering that the RWGs approximation of the SIWs may be not optimal for frequencies far from the center-band. In addition, the measurement is affected by the connector, and by fabrication tolerances..

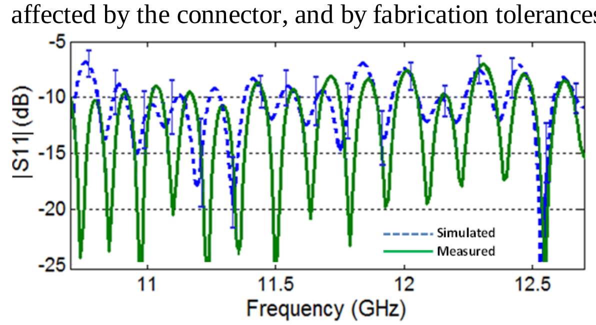


Fig. 4. Simulation (blue-dashed) and measurement (green-solid) of the reflection coefficient of the 352x352 mm^2 antenna. The bold blue curve is calculated with tanδ=0.0030, and the markers define a possible range for tanδ, i.e. [0.0030±0.0008].

The total gain of the antenna, *G*, is:

$$G(f)\big|_{dB} = D(f)\big|_{dB} + P(f)\big|_{dB}$$

where *f* is the frequency, *D* is the ideal directivity, that is approximated by the directivity of a uniform antenna-aperture of area *A*, i.e. $D = 4\pi A/\lambda^2$ (the actual field taper over the array is not perfectly uniform, so, in that sense, this is an estimation), and *P* is the fraction of the input power outgoing from the slots:

$$P = \sum_{i=1}^{Nslot} 2\,\mathrm{Im}\left(a_i b_i^*\right),$$

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where a_i and b_i are the scattering coefficients of the fundamental mode of the i-th slot, evanescent in the whole frequency range, for the chosen slot sizes. Here, the slot modes are defined as the field distributions in the slots, whose sections are seen as the sections of rectangular waveguides perpendicular to the plane of the antenna. As it is shown in Fig. 5, the simulated gain is 2÷3 dB higher than the measured one. This is likely due to the losses of the coaxial connector, to dielectric losses possibly higher than nominal ones, and, as mentioned above, to the not perfectly uniform field taper.

Figure 6 shows the radiation pattern of the antenna, and highlights its squint-free feature. The arrangement of the slot-pairs in the y-direction is such that these are not geometrically equivalent: this fact explains the different SLLs in E-plane (*yz*) and H-plane (*xz*).

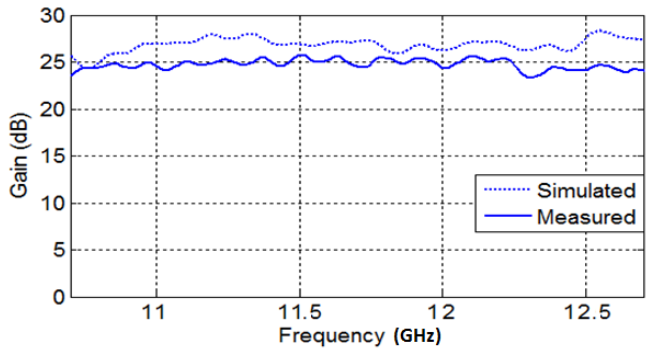

Fig. 5. Measured and simulate gain of the 352x352 mm^2 antenna.

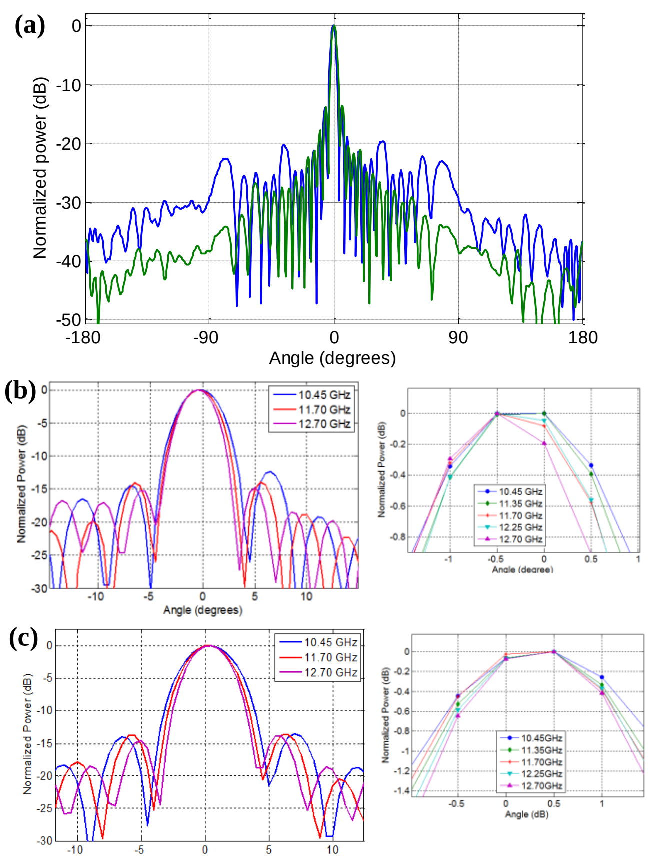

Fig. 6. a) Measured radiation pattern of the antenna at center band (11.7 GHz): E-plane (blue) and H-plane (green). b) Variation of the main lobe with frequencies, and respective zooms on the radiation peak: E-plane. c) Same as (b), but for the H-plane.

IV. Conclusion

A planar slotted array in SIW technology has been shown, made up on a single-layer substrate, featuring the frequency band of DBS communications, from 10.7 GHz to 12.7 GHz. The peculiarity of this work relies in the analysis of a very simple and thin antenna, made entirely of slotted SIWs, with a particular choice of the radiating elements. The latter are given by "H"-shaped SIW-terminations: this choice allows enlargement of the bandwidth, and broadside radiation with substantially squint-less main lobe.

References

[1] Y. L. Zhang, W. Hong, F. X, K. Wu and T. J. Cui, "Analysis of Guided wave Problems in Substrate Integrated Waveguides – numerical simulations and Experimental Results," *IEEE MTT-S International Microwave Symposium Digest*, pp.: 2049-52, 2003.

[2] L. Wan, W. Hong, C. Hua, J. Chen, K. Wu, "Simulation and experiment on siw slot array antennas", *IEEE Microwave and Wireless Component Letters*, vol. 14, no. 9, pp.: 446-448, Sept. 2004.

[3] M. H. Awida, A. E. Fathy "Substrate-Integrated Waveguide Ku-Band Cavity-Backed 2x2 Microstrip Patch Array Antenna*", IEEE AWPL*, vol. 8, pp.: 1054-56, 2009.

[4] R. Elliot. *Antenna theory and design*, IEEE press series on electromagnetic wave theory, 2003.

[5] T. Zhang, W. Hong, Y. Zhang, K. Wu, Design and Analysis of SIW Cavity Backed Dual-Band Antennas With a Dual-Mode Triangular-Ring Slot, *IEEE Trans. Ant. and Prop*., vol. 62, n. 10, pp. 5007-16, 2014.

[6] L. Jin, R. M. Lee, and I. D. Robertson, Design and Performance of Log-Periodic Substrate Integrated Waveguide Slot Antennas, *IEEE MTT-S International Microwave Symposium Digest*, pp.: 1-3, 2012.

[7] W. Liu, Z. N. Chen, T. S. P. See, and F. Liu, SIW-Slot-Fed Thin Beam-Squint-Free Fabry-Pérot Cavity Antenna With Low Backlobe Levels, *IEEE AWPL* vol. 13, pp. 552-4 2014.

[8] D. Cho, H.-Y. Lee, Folded Corrugated SIW (FCSIW) Slot Antenna for Backlobe Suppression, *IEEE AWPL*, vol. 12, pp.: 1276-79, 2013.

[9] J. Xu, Z. N. Chen, and X. Qing, CPW Center-Fed Single-Layer SIW Slot Antenna Array for Automotive Radars, *IEEE Transaction on antennas and propagation*, vol. 62, n. 9, pp.: 4528-36, 2014.

[10] M. Mbaye, J. Hautcoeur, L. Talbi, K. Hettak, Bandwidth Broadening of Dual-Slot Antenna Using Substrate Integrated Waveguide (SIW), *IEEE Antennas and wireless propagation lett.*, vol. 12, pages 1169-71, 2013.

[11] K. H. Badr, "Design and Implementation of Planar Microstrip Antenna Sub-Array for Satellite TV Reception", *Middle East Conf. on Antenna and Propagation (MECAP) IEEE*, Egypt, 2010.

[12] M. Ghiyasvand and K. I. Forooragh, "Design and Analysis of a 16 × 16 Microstrip Antenna for Direct Broadcast Satellite Reception,*13th ICEE2005*, 2, pp.: 589-594, 2005.

[13] K. F. Lee, and W. Chen, *Advances in microstrip and printed antennas*, New York, Wiley, 1997.

[14] Knyazev S., "Microstrip antennas and arrays on the suspended substrate", *Proceeding of 17th International Conference on Applied Electromagnetics and Communications, ICECom*, pp.: 168-171, 2003.

[15] M. Ghiyasvand, A. Bakhtiari, and R. A. Sadeghzadeh, "Novel microstrip patch antenna to use in 2×2 sub arrays for DBS reception", *Indian Journal of Science and Technology*, pp.: 2967-71, vol. 5, no. 7, 2012.

[16] [1] L. Wang, Y. J. Cheng, D. Ma, and C. X. Weng, "Wideband and dual-band high-gain substrate integrated antenna array for E-band multi-gigahertz capacity wireless communication systems," *IEEE Trans. Antennas Propagatopn*, vol. 62, no. 9, pp. 4602-4611, Sep. 2014.

[17] Y. J. Cheng, Y. X. Guo, and Z. Q. Liu, "W-Band large-scale high-gain planar integrated antenna array," *IEEE Trans. Antennas Propagation*, vol. 62, no. 6, pp. 3370-3373, Jun. 2014.

[18] L. Josefsson, "Analysis of Longitudinal Slots in Rectangular Waveguides", *IEEE Transactions on Antenna and Propagation*, vol. AP-35, no. 12, pp.: 1351-7, 1987.

[19] S. R. Rengarajan, M. Steinbeck., "Longitudinal slots in dielectric filled rectangular waveguides", *Antennas and Propagation Society International Symposium*, vol. 2, pp.: 1276-1279, 1991.

[20] A. Morini, T. Rozzi, and G. Venanzoni, "On the Analysis of Slotted Waveguide Arrays", *IEEE Transactions on antennas and propagation*, vol. 54, no. 7, pp.: 2016:21, 2006.