Fully Planar CSRR-SIW Slot Antennas of Optimized Gain and Enhanced Bandwidth for Millimeter Wave and 5G Communications

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Abstract— **We present fully planar, low-cost and easy to fabricate slot antennas which operate at two different frequency bands. The designs are based on the CSRR-SIW concept, which is a strong alternative for cost-effective implementation for millimeter circuits and antennas. The proposed antennas exhibit very competitive characteristics in terms of their bandwidth and gain.**

Keywords—Substrate Integrated Waveguides, slot antennas, 5G Communications, fully planar structures

I. INTRODUCTION

The design of 5G wireless networks calls for the utilization of the until now underused millimeter wave frequency bands. This results in a growing need for new reliable and cost-effective microwave components capable of supporting millimeter wave applications. In this context, the Complementary Split Ring Resonator based Substrate Integrated Waveguide (CSRR-based SIW) has been proposed [1] as a viable candidate offering low loss propagation and low-cost manufacture.

This novel transmission line, which is a planar alternative to the standard Substate Integrated Waveguide, is realized by replacing the metalized via holes inside the substrate by two-dimensional complementary split ring resonators etched on the metal plates terminating the dielectric substrate. By this means, a virtual metamaterial electric wall is created, capable of offering a low-loss channel for wave propagation [2]. In this paper, we further proceed to exploit this synthesized waveguide as a building element to propose totally planar slot antennas, using the proper optimization procedures in order to operate at specific frequency bands with directive radiation patterns.

A. *The fully planar structure of a CSRR-SIW*

The basis structure on which we design the proposed planar antennas is the CSRR-SIW, described in detail in [1,2]. It is an alternative design of a classical SIW, where the vias are replaced by complementary SRRs producing an electric wall and eventually a channel where the electromagnetic field propagates. Fig. 1 shows the details of the Complementary SRR used whereas Fig. 2 depicts the unit cell of the CSRR-SIW and its geometric parameters. The details of the design are presented in Table I for the configurations at both frequency bands of 10-12 GHz and the lower 5G band with a central frequency of 27 GHz.

TABLE I. SIW DIMENSIONS

Frequency (GHz)	Outer ring (mm)	Inner Ring (mm)	Ring Gap (mm)	SIW width (mm)	Substrate height (mm)
10	1.8	1	0.6	16.8	0.508
27	0.84	0.54	0.3	6.5	0.8001

B. *CSRR-SIW Slot antenna and Field distributions around the slots*

The first proposed antenna structure is depicted in Fig. 3. It consists of 7 slots opened at the upper side of a CSRR-SIW. The width of the slots is about $\lambda_g/20$ and the length of the slots is tapered from 0.1 λ_0 to 0.4 $\lambda 0$, where λ_g is the guided wavelength and λ_0 is the free space wavelength at a central simulation frequency respectively. The spacing between the slots is equal to $\lambda_g/2$ and the chosen PCB circuit board is an RT/ Duroid laminate of h=0.508 mm with a relative dielectric constant ε_r=2.2 and tanδ=0.001.

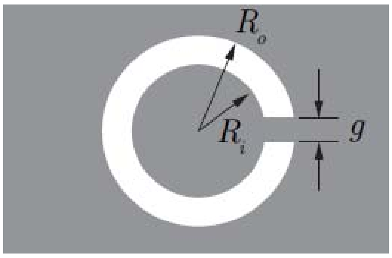

Fig. 1. Details of CSRRs' structure (only the upper ring is shown - the other one is placed on the other side of the PCB, rotated 180 degrees).

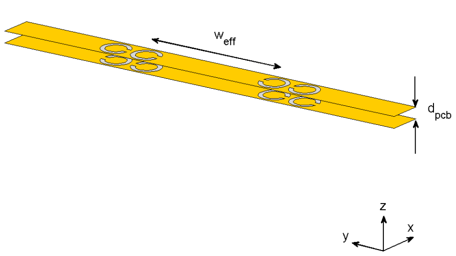

Fig. 2. Unit cell (slice) of the CSRR-SIW and its geometric parameters

The reason for the slot length tapering is the matching of the impedances of the antenna and the feeding cable, in order to achieve return loss less than 10 dB [3, 4, 5]. The geometric parameters used in the optimization procedure were the slot distance, the slot length and the slot tapering factor. The optimized results of this parametric optimizations are depicted in the following pictures. In Fig. 4 we show the return loss of the antenna in terms of its S_{11} parameters. It is easily seen that the antenna works properly above 10.75 GHz. Furthermore, the 3d radiation pattern at 12 GHz is shown in Fig. 5. The antenna exhibits a directive far field behavior with a maximum gain of approximately 7 dBi at the aforementioned frequency.

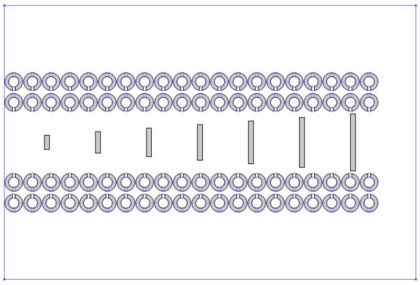

Fig. 3. Upper view of the proposed CSRR-SIW 7-slot antenna

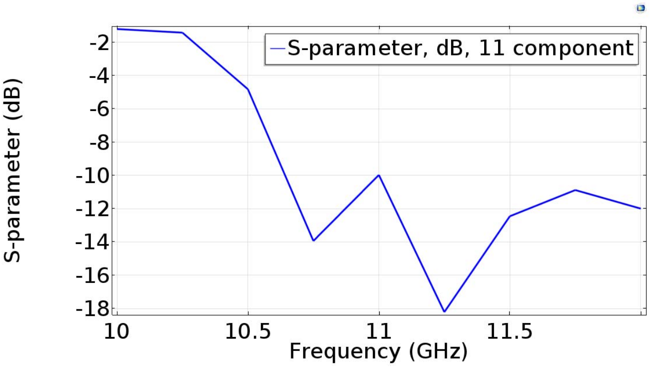

Fig. 4. Return loss of the proposed CSRR-SIW 7-slot antenna

It is very important to have a clear view of the near field distributions around the slots, in order to explain and standardize the mechanisms that produce these specific directional far field radiation patterns. Although there might be analytical formulas for the basic parameters of slot antennas [6, 7], we conclude from the simulations that there is a need of many optimization processes including some crucial geometric parameters in order to achieve the proper feeding of the slots and -as a result- the suitable far-field they produce. As an example, we plot the power flow in terms of the average Poynting vector in the middle of the substrate for the frequency of 12 GHz in Fig. 6.

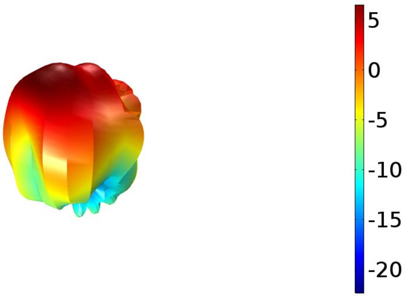

Fig. 5. 3d radiation pattern of the proposed CSRR-SIW 7-slot antenna at 12 GHz

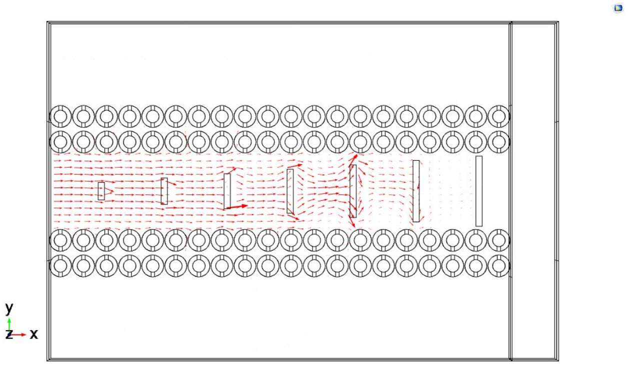

Fig. 6. Power flow in the mid-substrate of the antenna at f=12 GHz

II. CSRR-SIW Apperture Expanded Slot Antenna Design for 5G Communications Frequency Bands

In order to enhance the proposed slot antenna we present a novel antenna design depisted in Fig. 7. It consists of a part of a CSRR-SIW which operates at 5G Communications lower band (26-28 GHz), which is expanded in a horn-like manner from w_{eff}=6.5 mm to w_{eff}'=21.5 mm. There are two arrays of 9 tapered slots opened at an angle of 15 degrees. The geometric parameters used in the optimization procedure were the slot distance, the slot length, the angle between the arrays and the slot tapering factor. The following pictures show the optimized results. Fig. 8 shows the S_{11} parameters versus frequency, whereas Fig. 9 depicts the far-field radiation pattern at the frequency of 27.5 GHz. We can see that this antenna operates at frequencies greater than 27.2 GHz, whereas it exhibits a maximum gain of approximately 10 dBi at 27.2 GHz.

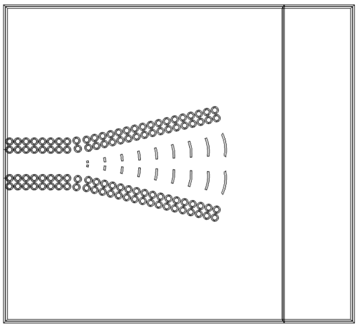

Fig. 7. Upper view of the proposed CSRR-SIW apperture-expanded slot antenna

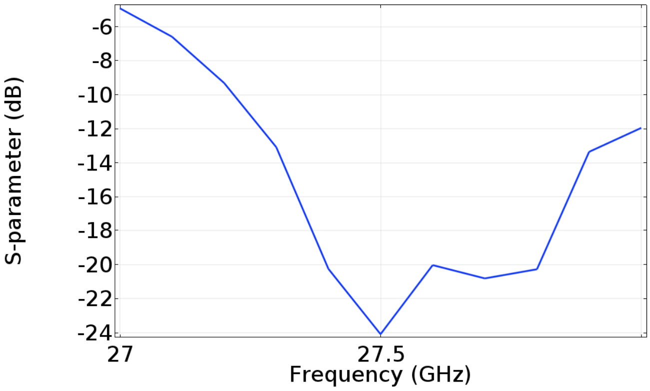

Fig. 8. Return loss of the proposed CSRR-SIW apperture-expanded slot antenna

ACKNOWLEDGMENT

This research is carried out / funded in the context of the project "Development and implementation of an integrated platform for fully planar low-cost circuits for 5G, Internet-of-Things and THz Communications technologies" (MIS 5005207) under the call for proposals "Supporting researchers with emphasis on new researchers" (EDULLL 34). The project is co-financed by Greece and the European Union (European Social Fund- ESF) by the Operational Programme Human Resources Development, Education and Lifelong Learning 2014-2020.

Ευρωπαϊκή Ένωση
European Social Fund

Operational Programme
Human Resources Development, Education and Lifelong Learning
Co-financed by Greece and the European Union

ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη

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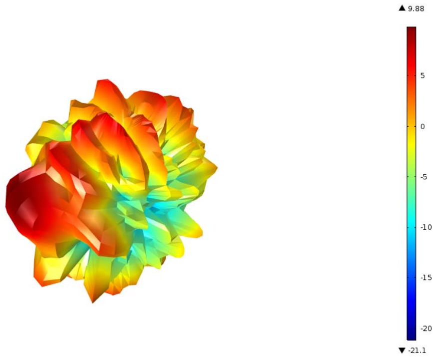

Fig. 9. 3d radiation pattern of the proposed CSRR-SIW apperture-expanded slot antenna at 27.2 GHz