Analysis and Design of Dual-Polarization Antennas for Wireless Communication Systems

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Abstract**—**The paper describes the design and simulation of dual-polarization antennas that use the resonance and radiating properties of the H_{00} mode of metal open waveguides. The proposed antennas are formed by two orthogonal slots in a finite conducting ground plane. The slots are backed by metal screens connected to the ground plane forming open waveguides. It has been shown that the antenna designs can be efficiently used in mm-wave bands. The antenna single mode operational bandwidth is higher than 10%. The antenna designs are very simple and low-cost. They allow flush installation and can be efficiently used in various communication and remote sensing devices on fast moving carriers. Mutual coupling between antennas of the proposed design is very low. Thus, multiple antenna structures with proposed antennas can be efficiently employed in multi-band and in multiple-input-multiple-output (MIMO) systems.

Keywords**—**Antenna, antenna arrays, multiple-input-multiple-output, MIMO, millimeter wave bands, slot antenna, flush installation, directivity, open waveguide, conformal antennas.

I. Introduction

THE high-performance level of the fifth generation of wireless networks will impose very stringent and challenging demands on the antenna characteristics. Conventional antenna design techniques may not be applicable, or the parameters and efficiency of antennas formed by well-known and often used elements such as dipoles and patches could not be acceptable.

The wireless MIMO communication systems require low profile, wide bandwidth, high isolation antennas that maintain good performance. The design of small antennas with lowest mutual coupling remains one of the main challenges in employing MIMO systems in portable devices [1].

In this paper, we consider antennas that belong to the class of antennas that utilizes the properties of open waveguides formed by conductive cylindrical screens. The antennas of this class can be efficiently used in 5G communication systems as a single antenna as well as elements in antenna arrays.

Cylindrical structures with open cavities can have a resonance when the cross-sectional dimensions are considerably smaller than the wavelength. Low frequency resonance properties of cylindrical screens with longitudinal slots have been studied in [2], [3]. It was demonstrated in [4], [5] that infinite slotted circular cylinders can lead to passive super-directive arrays. If we consider an open cylindrical screen as a waveguide, the low frequency resonance corresponds to the cut off frequency of H_{00} mode. Consequently, when an antenna has a cylindrical screen attached to the conducting plane with a longitudinal slot and the dimensions of the screen are such that only the H_{00} mode exists, the radiation properties of the slot change dramatically. Closed cylindrical waveguides do not support the H_{00} mode – the corresponding eigenfrequency is 0 and the eigenfunction solution is trivial.

Open Waveguide Antennas formed by a single cylinder with a longitudinal slot were presented in [6], [7]. It has been shown that the antennas allow flush installation and can be efficiently used either as a single radiating element or as an element in antenna arrays. It was demonstrated that the radiating H_{00} mode of the waveguide produce uniform field distribution along the slot and as the consequence, form optimal directivity. Wide band millimeter wave antenna arrays formed by conductive cylindrical screens with longitudinal slots were proposed in [8]. It was demonstrated that the number of radiating elements in arrays can be minimized using optimal directivity of the elements caused by uniform field distribution along the slots. For example, the 8-element open waveguide antenna array with dimensions 210x840 mil (5.334x21.336 mm) has the realized Gain is 16.88 dB at 60 GHz when the theoretical maximum (without super-directivity) is ≈17.5dB.

The millimeter waves with frequencies above 20 GHz are characterized with very high path losses comparing to electromagnetic waves in low gigahertz communication spectrum bands. To compensate the losses, the millimeter wave technology should use antennas with high directional gain. The wavebands that are open for licensed or unlicensed communication have the bandwidth > 10%. Wideband antennas usually combine several excitation modes at close frequencies to have low reflection loss. It is desirable to have a single-mode wideband antenna with a stable shape of the radiation pattern within the operational frequency band.

Another requirement for modern antennas is that the antennas should allow flush mounting and, ideally, conform the surface of a vehicle. Conformal phase array antennas are often designed using slots of various shapes as radiating elements. This requirement is critical for the fast-moving carriers such as aircrafts, drone, missiles, etc.

Slot antennas are usually designed to transmit or receive polarized EM signals. A slot in a conductive plane could be considered as a magnetic current dipole. The efficiency of the communication in this case depends on the mutual orientation of the receiving and transmitted antennas. Since it is impossible to predict the antenna orientation on a mobile device, it is desired to have antennas that can receive/transmit signals with orthogonal polarization.

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In this paper, we propose antennas that have a conductive plane with two orthogonal slots that cross each other in the middle. There are two metal cylindrical screens that also cross each other in the middle. The metal screens together with the antenna ground plane compose open waveguides that form uniform distribution of the magnetic current along the slots and at the same time increase the isolation of the antenna and reduce energy loss to surrounding componentry and environment. In order to demonstrate the effectiveness of using the designed antennas in MIMO multiple antenna systems, the mutual coupling between closely located antennas has been analysed.

II. Antenna Configuration

A. Antenna Design

To create an antenna that can efficiently receive/transmit EM signals of both polarization, we use two open waveguide sections that go in orthogonal directions. The antenna is formed by a finite conductive plane with two slots that go in orthogonal directions and four open metal cylindrical screens (Figs. 1 and 2).

The metal cylindrical screens are electrically connected with the conductive plane. The screens and the portion of the conductive plane with slots form four open waveguides. The antenna feed is located across the two opposite corners of the slot cross.

In this case, we used the cylindrical screens with rectangular cross-section. The cross-sectional dimensions of the screens were chosen to have the H_{00} mode cut-off frequency in the open waveguides smaller than the frequencies in the antenna operational band.

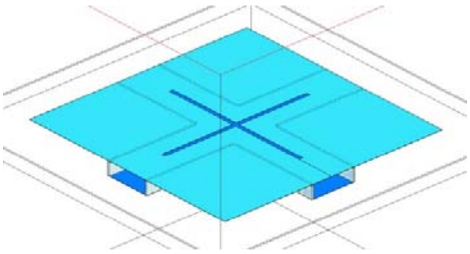

Fig. 1 Dual Polarization antenna design

Since the radiation is coming from the slot, the antenna can be classified as a slot antenna. However, we do not employ the commonly used concept that the thin slot in an infinite ground plane is the compliment to a dipole in free space, i.e. the slot in the open waveguide antenna is not a magnetic dipole. The antenna operates more like a leaky-wave antenna and the length of the slots is bigger that λ0/2 (λ0 – is the wavelength of the radiation in free space). In contrast with conventional cavity-backed slot antenna designs, the considered antenna design does not use cavity resonances.

The antenna can be excited by a coaxial cable with the ground and central conductor connected to the opposite corners of the cross-point of the slots correspondingly. A microstrip feed can also be efficiently employed if we use antenna upper plane as the ground and place the microstrip above or below the plane. The microstrip line should continue under or above the cross-point of the antenna slots and be connected by a via to the antenna plane (Fig. 3).

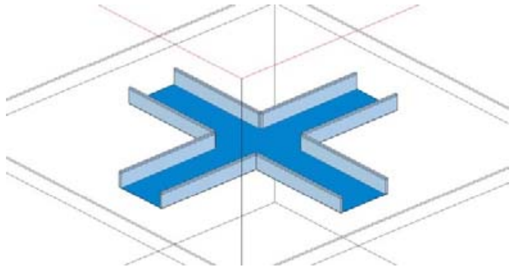

Fig. 2 Lower parts of the Dual Polarization antenna design that form the open cylindrical waveguides (the upper ground plane with the slots is invisible on this figure)

B. Design Procedure

- Using the specified antenna operation frequency band, we need to choose the cross-sectional dimensions of the screens that are big enough to support the radiating H_{00} mode in the antenna open waveguides.
- The slot length should be close to the wavelength at the center of the operation frequency band (λ_0). The field distribution along the slot should be as uniform as possible.
- Use the direct feed at the cross-point of the slots from a 50 Ohm transmission line with/without a matching transformer.
- The $|S11| \leq 10$ dB bandwidth of the antenna should be better that 10%.

III. Results and Discussion

An antenna formed by a copper plane with two slots crossed symmetrically at 90^o angle, and copper screens with rectangular cross section were optimized to work in the 28 GHz frequency band. The slots are parallel to X and Y axes correspondingly. Various versions of the antenna were simulated, and the dimensions of the slots and screens were optimized.

The considered design can be used as a radiation element in a bigger phased antenna array. A variety of scenarios with single (Figs. 1 and 2) and multiple radiating elements were considered.

The antenna length along x-axis Lx and y-axis Ly is 15.24 mm (600 mils) and the cross-sectional dimensions of the cylindrical screens are 3.048 mm and 1.016 mm. The thickness of the antenna is defined by the cross-sectional dimension of the cylindrical screens along Z-axis and it is 1.016 mm. The optimal slot length is 10.16 mm. In this case, we design a 28 GHz antenna, thus we need to keep the antenna input impedance close to 50 Ohm within the operation frequency band from 26.2 GHz to 29.0 GHz. The $|S11| \leq 10$ dB bandwidth of the antenna is 10.25% (Fig. 4). Antenna feed is formed by a segment of a microstrip line on the RO4350B (Rogers) substrate and a via that connects the microstrip to the upper ground plane (Fig. 3). The microstrip line has a narrow segment with optimized width that goes diagonally under the slot-cross and is connected to the ground plane at the opposite corner. In antenna array, corporate feed network can be designed using microstrip lines that can be located inside the cylindrical screens.

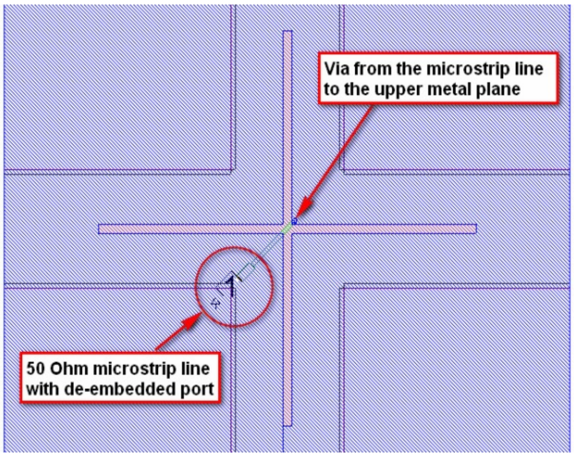

Fig. 3 Antenna feeding structure with 50 Ohm microstrip line, matching segment and via

The antenna array returns loss and VSWR as the functions of frequency are presented on Fig. 4.

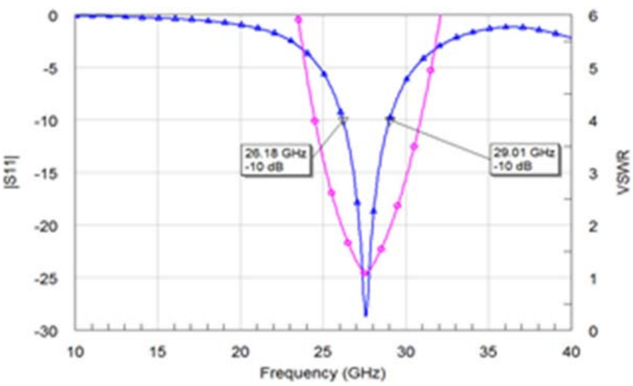

Fig. 4 Dual Polarization antenna for 28 GHz. Return loss and VSWR versus frequency

We use a single resonance mode and the radiation pattern remains the same at all frequencies within the operation band.

The radiation into the lower hemisphere is reduced by more than 10 dB and in case of the antenna flush installation (the upper ground plane is bigger and bent), the back radiation will be reduced. The radiation patter of the antenna is presented in Fig. 5.

Antenna arrays formed by multiple dual polarization elements have been analyzed. Particular attention has been paid to the mutual coupling between antenna elements. When antenna array elements are located in the checkerboard fashion, the mutual coupling can be below –40 dB (Fig. 6). When the designed antennas overlap to be placed together in as dense as possible array, the mutual coupling increases, but still can be as low as –26 dB (Fig. 7).

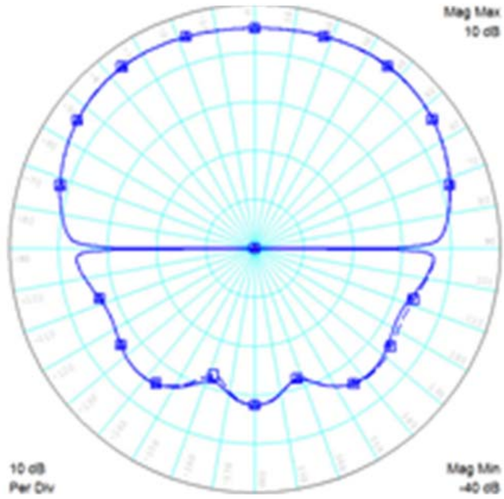

Fig. 5 Dual Polarization antenna for 28 GHz. Radiation patter of the antenna (solid line –XZ plane and dashed line – YZ plane). The directivity is 5.0dBi

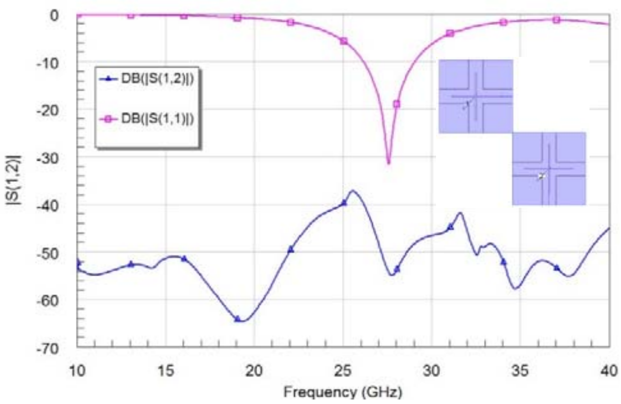

Fig. 6 Dual Polarization antenna array. Return loss and mutual coupling between antenna elements

IV. Conclusion

Dual Polarization radiating elements for a class of efficient conformal antennas have been studied. The present work has shown that antennas formed by two crossed slots in a conducting plane and cylindrical screens that backed the slots, have very good matching properties and can form efficient radiation patterns in both X and Y planes. The magnetic current distribution along the slot is close to uniform and consequently the antenna directivity is close to optimal. It has been shown that the physical phenomena responsible for the field distribution are related to propagation and radiation of the H_{00} mode waves in the open waveguide. The considered antennas allow flush mounting and the antenna plane can be designed to conform a shape of fast moving vehicles, aircraft or drone fuselages, etc.

It was demonstrated that the single mode operational bandwidth of the antenna in 28GHz band is > 10% and the mutual coupling between the designed antenna elements can be dropped below -40 dB. The obtained results show that the proposed dual polarization antenna can be efficiently used in 5th generation (5G) communication systems including MIMO antenna arrays.

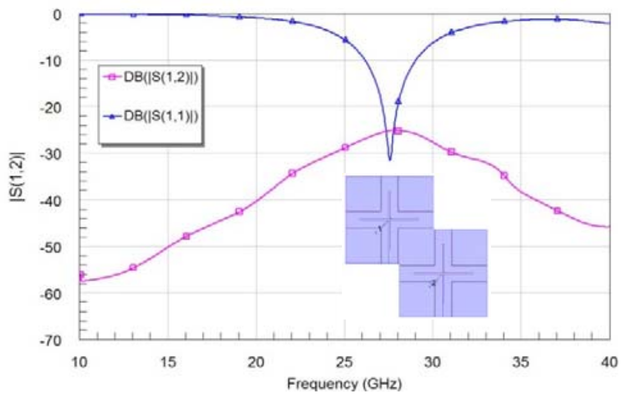

Fig. 7 Dual Polarization antenna array. Return loss and mutual coupling between antenna elements (dense array)

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