Multifunctional slot antennas

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Abstract. A variant of a broadband antenna is proposed, which can combine up to four antennas with different polarizations and operating frequencies in one design. The antenna is formed in the shape of an annular slot (annular magnetic current) excited at four points through a quarter of the slot perimeter. The characteristics of directivity and VSWR obtained as a result of numerical simulation using the 4NEC2 software product are presented.

1. Introduction
To increase the information transfer rate and improve the quality of transmitted information in communication or radar systems, spatial, frequency or polarization separation is used, allowing the signal to be transmitted simultaneously through several channels. One of the ways to increase bandwidth is to use multiple transmitting and receiving antennas (MIMO – Multiple Input Multiple Output) [1]. In communication systems, the receiving and transmitting channels are also usually separated in frequency and polarization [2, 3]. The dimensions of a MIMO antenna containing several antennas with different characteristics, as a rule, exceed two wavelengths, which in some cases is unacceptable. In this regard, it is interesting to study antennas that allow emitting and receiving signals of different polarization at different frequencies simultaneously and independently.

In the antennas with elliptical polarization, electric current emitters are usually used: dipoles or loops. To obtain circular polarization, turnstile antennas are used representing crossed dipoles excited with a phase shift of ±90 degrees, or a combination of a loop with a dipole located along the one axis [4]. In addition to dipoles, a turnstile antenna contains two balanced-to-unbalanced units (balun) and the summation unit. The same units are contained in antenna consists of combination of the loop and the electrical dipole. The implementation of such structures using printing circuit board technologies is difficultly in the microwave range.

2. Numerical model of the antenna
Slot antennas allow simplifying the design and extending the functionality. Slot antennas can be considered as the analogues of magnetic currents emitters. A slot cut in a finite metal screen is a complementary structure for a plane metal dipole that has the same shape as the slot. The slot antenna can be optimized as a complementary structure of the dipole antenna (conductive material and air are interchanged) by applying Babinet-Booker’s principle [5]. The major interpretation of this principle is defined as: the E field around a metallic strand is equivalent to the H field created by a slot with the same dimensions inside an infinite ground plane. According to the Babinet-Booker’s principle such complementary structures are characterized by the facts:
a) the forms of their antenna patterns coincide,
b) the polarization of electric field produced by the metal emitter is orthogonal to the polarization of electric field produced by the slot emitter,
c) the impedance $Z_m$ of the metal emitter is related to the impedance of a slot emitter radiator $Z_s$ by the ratio: $4Z_mZ_s = W_0^2$, where $W_0$ is the wave impedance of the surrounding medium.

These properties of complementary structures are strictly enforced only for the infinite ground screen. If the screen size is comparable to the size of the slot emitter, the forms of the patterns and the ratio of the impedance of self-complementary structures may differ significantly. For example, let’s take a slot emitter that is complementary to a metal dipole with the arms which are the plates with the dimensions of 0.1x0.1 of the wavelength. Such slot emitter is well-matched with a 150-Ohm feeder and has a gain that is 1.5÷2 dB greater than the gain of the electric dipole. At the same time, a balun is not required to excite the slot, which significantly simplifies the design of the slot emitter.

The proposed version of the antenna is based on the duality principle that is applied to the wire ring emitters. The wire has been shaped as a circle or a square with a perimeter equal to the wavelength. According to the duality principle, the complementary antenna is a slot in the shape of a square, cut in a metal plate. To simplify the model used in numerical simulation, a square shape of the slot is chosen. A variant of the magnetic current emitter design suitable for printing circuit board technology is shown in (Figure 1a). The emitter is a square plate of double-sided foil dielectric. The outer and inner parts of the metal plate with respect to the slot are placed on different sides of the dielectric. This allows to change the impedance of the slot in a wide range and to match the emitter with feeder. The microstrip line is attached to one side of the square slot, so that the strip of the line crosses the slot and connects to the inner part of the metal plate. Analytical calculation of such emitters presents severe difficulties. So, to determine the antenna characteristics, the 4NEC2 free software package designed to simulate wire structures was used. The wire model used to simulate a slot emitter is shown in (Figure 1b).

![Figure 1. A variant of the slot emitter design (a) and its wire model for the 4NEC2 software (b)](image)

When using such an emitter as an independent antenna, no counterweight elements or baluns is required. If the emitter is used as an antenna array element or as the feed antenna of a parabolic
reflector, its pattern should be unidirectional, i.e. have only one main maximum lobe. For this purpose, a printed circuit board of the emitter is located over the metal screen at a distance of 0.15 ÷ 0.25 of the wavelength. A metal cylinder of round or square cross-section is inserted between the screen and the metal plate which is internal to the slot.

Excitation of the emitter is carried out by a segment of the strip line, one end of which is connected to the outer edge of the slot and another to a segment of the coaxial line. The output of this coaxial line forms the antenna port. The coaxial segment is placed inside a hole drilled in a metal insert (Figure 2a). If creating ports for each side of the square, a square slot allows to excite four different signals: two anti-phase signals of vertical polarization and two anti-phase signals of horizontal polarization. This extends the functionality of this type of a magnetic current emitter.

A variant of the emitter design with advanced functionality is shown in (Figure 2b). Such antenna provides transmission of a signal with linear vertical polarization (port 1), a signal with linear horizontal polarization (port 2), and a signal with circular polarization (port 3) at different frequencies within the matching band. Circular polarization is formed due to the fact that the middle point of the internal edge of the square slot horizontal side is connected to the middle point of the internal edge of the square slot vertical side by a quarter-wave segment of the strip line.

3. Results of numerical simulations

Simulation results of the emitter made according to (Figure 1a) and to (Figure 2a) are shown in (Figure 3), which presents the frequency dependence of voltage stand wave ratio (VSWR) and angular dependence of the antenna gain $G$. For the antenna with a 15×15-mm square plate made according to (Figure 1a) the relative matching bandwidth of the emitter exceeds 20% and the shape of the pattern is kept stable in the frequency range from 8 to 12 GHz.

When a horizontal side of a square slot is excited, the vertical polarization field is radiated. When a vertical side is excited, then the horizontal polarization field is radiated. Frequency dependence of VSWR of unidirectional emitter with linear polarization (Figure 2a) and the pattern of such emitter at 10 GHz is shown in (Figures 3a and 3b) by dotted lines. One can see that in this case the antenna matching band expands significantly. This can be explained by the fact that in the presence of a metal insert, such an antenna can be considered as a combination of an electric pin with a capacitive load and a circular slot, i.e. a combination of electric and magnetic emitters, which usually results in the matching band expansion [6].

\[ a) \quad b) \]

\[ A \quad A-A \quad 2 \]
\[ 3 \quad 1 \quad B \quad B-B \]

Figure 2. Design variants of a unidirectional vertical polarization antenna (a) and a multifunctional antenna providing reception and transmission of two signals with orthogonal linearly polarized polarization and a circular polarization signal (b)
Directional characteristics of the multifunction slot emitter shown in (Figure 2b) are presented in (Figure 4). The proposed antenna has three ports. The excitation of each single port allows generating electromagnetic fields of different polarizations. The solid line (Figure 4a) shows the radiation pattern corresponding to port 1 which forms a vertical polarization field. The dotted line corresponds to the horizontal polarization field generated by the excitation of port 2. The field directivity characteristics generated when a signal is sent to port 3 are shown in (Figure 4b). Unused ports are loaded by 50-Ohm matching resistors.

Figure 4. Directional characteristics of a multifunctional slot emitter. Solid line is the vertical polarization pattern (a), normalized circular polarization pattern (b). Dotted line is the horizontal polarization pattern (a), axial ratio (b)

4. Summary
The simulation results show that the use of slot antennas as the analogues of magnetic current emitters allows to organize up to four radio channels with different types of polarization in C and X band with a bandwidth of two octaves or at least 500 MHz. In radio channels with circular polarization in the
specified frequency band the axial ratio of the emitter exceeds 0.8. The proposed variant of magnetic current emitters has a fairly simple design and is suitable for use in 5G and WiMAX communication systems.

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