A Compact CP Mode Converter Antenna

Seyed Jalil Hosseini

Abstract – **In this article, a mode converter antenna (MCA) with a left-handed circular polarization (CP), is designed and simulated at 10 GHz frequency. The circularly polarized mode converter antenna (CPMCA) consists of four inner conductors and a body. In the proposed antenna, the TEM mode is converted into a CP TE_{11} mode, by using the inner conductors connected to the coaxial waveguide in two vertical and horizontal directions. The sidelobe level is less than -11 dB at the working frequency. The S_{11} and axial ratios of the CPMCA are about -16.8 and 0.43 dB, respectively. Furthermore, the axial ratio is in the acceptable range.**

Keywords – **Mode converter antenna, Circularly polarized mode converter antenna, Compact mode converter antenna, Circularly polarized TE_{11} mode, TEM-TE_{11} mode converter, High-power microwave antenna, HPM mode converter antenna.**

I. Introduction

Electromagnetic diodes are the systems that can convert voltage and current into waves [1]. The conversion is generally done at very high power. Some electromagnetic diodes cannot be used effectively due to their non-applicable output field shape [1] and [2]. In some electromagnetic diodes such as coaxial-VCO [3-6] and MILO [7-11], the output fields are in the TM_{01} and TEM modes, respectively. Now, if these two types of diodes direct the free space with a conical horn antenna or an open-ending waveguide, the shape of the radiation pattern will be donut-shaped [6] and [8]. Therefore, its radiation pattern cannot effectively target one point. The best radiation pattern to target one point is a directive radiation pattern. Also, to get a directive radiation pattern, a TE_{11} mode is required [12]. Therefore, it should try to have the output electric field of an electromagnetic diode in this mode.

A Vlasov mode converter antenna can convert a TM_{01} mode to TE_{11} mode by using a diagonal cut-off or step in a circular waveguide [13-16]. The main problem of the structure is a deviation of about 30 degrees from the bore-sight, which makes it unsuitable in many applications. Of course, the use of reflectors can alleviate this problem to some extent, but it makes the structure non-compact. Another problem is that the polarization of its output field cannot be circular. A coaxial beam-rotating antenna (COBRA) can convert a TM01 mode to TE_{11} mode [17-21]. The key problem of the structure is the use of dielectrics, which increases the losses, especially at high power. Also, the antenna has large sidelobes. The other common MCA is the sectorial mode converter [1], [7], [9-10], and [22-23]. The structure can be converted from TEM mode to TE_{11} one. The key problem of the MCA is that the polarization of its output field cannot be circular. Unlike many linear mode converters, there are few circular mode converter antennas. In [24], a mode converter consists of a TM_{01}-TE_{10} mode coupler, a TE_{11}-TE_{10} mode coupler, and four phase-shifters are investigated at 9.6 GHz frequency. Its overall axial dimension is about 300 mm. The mode converter is not a compact structure. In [25], a reflector with a periodic structure fabricated on the dielectric printed board was investigated. The structure is not suitable for high-power microwave (HPM) applications. In [26] and [27], sectorial MCA is investigated. Their sidelobe levels are significant. Furthermore, if the operating frequency increase, the axial length of the antenna will increase due to the proximity of two propagation constants. Therefore, these MCA is not suitable for high frequencies. In this article, an MCA that can convert TEM mode to CP TE_{11} mode is presented. The antenna has good power handling and compactness.

In [28], the presented mode converter consists of a TM_{01}-TE_{10} mode coupler, a TE_{11}-TE_{10} mode coupler, and four phase-shifters. This can convert the TM_{01} mode to TE_{10}. In the structure, many bulky waveguides are needed. Hence, the mode converter is not compact and applicable. In Table 1, the proposed structure is compared with the previous MCAs.

A TM_{01} to TE_{11} converter is presented in [29]. The MC antenna can provide a directional pattern with circular polarization using vertical and diagonal blades installed in its aperture. In addition to the complexity of structure, the antenna cannot withstand high power because using blades dramatically increases the likelihood of an electrical breakdown effect. In addition, due to the installation of blades in the horn antenna aperture to increase the antenna gain, the designs change.

To overcome these limitations, a compact, high-power, and simple structure is proposed. The antenna can withstand a lot of power due to its all-metal and large cross-section.

This paper is organized as follows: Section II presents the theory of the proposed antenna. In Section III, the antenna has been designed. Section IV reports some numerical studies which are used on the antenna features and Section V reports the results of antenna simulated and optimized. In Section VI, Previous MCAs are compared with this work. Finally, the conclusion is presented in Section VII.

II. Theory of CPMCA

A. TEM-TE_{11} Mode Converter

An electric current, flowing in a coaxial waveguide, can create a magnetic field around the inner conductor. If the waveguide is only in the TEM mode, the magnetic field will be only a component of φ. There will also be a radial electric field. If the inner conductor is connected vertically to the outer conductor, the electric current will flow to the outer conductor (See Fig. 1).

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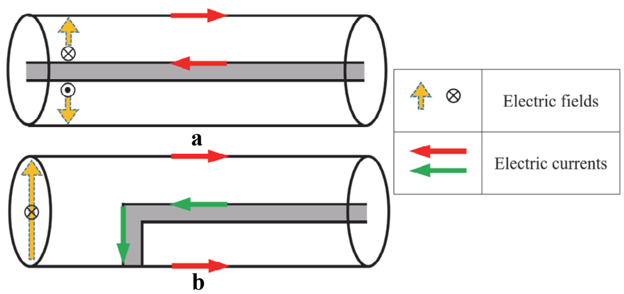


Fig. 1. Electric currents, magnetic and electric fields (a) in the coaxial waveguide and (b) in the proposed structure

In Fig. 1(a), note in a coaxial waveguide, the electric and magnetic fields are as follows [30]

$$\vec{E} = \frac{V_0}{r \ln\left(\frac{b}{a}\right)} \hat{a}_r$$
$$\vec{H} = \frac{V_0}{r\,\eta_0 \ln\left(\frac{b}{a}\right)} \hat{a}_\varphi \tag{1}$$

where η_0 is wave impedance in a vacuum and equals 377 Ω, a and b present the inner and outer radius of the coaxial waveguide, respectively, and V_0 is equaled $Z_0 I$ and here Z_0 represents line impedance in a vacuum and it is as follows [30]

$$Z_0 = 60 \ln\left(\frac{b}{a}\right) \tag{2}$$

Therefore, in a coaxial waveguide, the radial electric field and the rotating magnetic field be generated. By connecting the inner to the waveguide body, the electric current can induce a parallel electric field -Of course, the dimensions of the waveguide must be appropriate.- Note that if the operating frequency of the waveguide exceeds the value of (3), it is possible to incite the TE_{11} mode in a coaxial waveguide [30]

$$f_c = \frac{c}{\pi(a+b)} \tag{3}$$

where, c is lightspeed.

However, the CPMCA does not need to incite higher modes in the coaxial part of the structure. In the circular waveguide section, the TE_{11} mode is incited. In Fig. 1(b), the electric and magnetic fields in the circular waveguide are as follows [33]

$$H_r = -\frac{j\beta}{h} A\, J'_1(hr) \cos\varphi$$
$$H_\varphi = \frac{j\beta}{h^2 r} A\, J_1(hr) \sin\varphi$$
$$E_r = \frac{j\omega\mu}{h^2 r} A\, J_1(hr) \sin\varphi \tag{4}$$
$$E_\varphi = \frac{j\omega\mu}{h} A\, J'_1(hr) \cos\varphi$$

where β represents the phase constant and $h = 1.841/b$.

Note that return loss should be acceptably low. The return loss here occurs mainly due to the impedance mismatching between the coaxial waveguide and the circular waveguide in two different modes. This is presented in [30] as

$$S_{11} = 20 \log \left| \frac{Z_{TE_{11}} - Z_{TEM}}{Z_{TE_{11}} + Z_{TEM}} \right| \tag{5}$$

Now, if the acceptable value for S_{11} is −10 dB, we have

$$20 \log \left| \frac{Z_{TE_{11}} - Z_{TEM}}{Z_{TE_{11}} + Z_{TEM}} \right| < -10$$

$$\left| \frac{Z_{TE_{11}} - Z_{TEM}}{Z_{TE_{11}} + Z_{TEM}} \right| < 0.32$$

we know $Z_{TE_{11}} > Z_{TEM}$, then

$$\frac{Z_{TE_{11}}}{Z_{TEM}} < 1.94$$

By wave impedance of the circular waveguide in TE mode (6), and $Z_{TEM} = \eta_0$ we have

$$Z_{TE_{11}} = \frac{\eta_0}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}$$

$$\frac{f_c}{f} < 0.86$$

So,

$$b > \frac{134.426}{f} \text{ [mm]}$$

According to the impedance of the coaxial line (2) and the external conductor diameter (b), we can calculate the coaxial waveguide core diameter (a).

$Z_{TE_{11}}$ and Z_{TEM} indicate the wave impedances of the circular and coaxial waveguides in their dominant modes, respectively.

B. *Polarizing MCA*

To polarize MCA, the electric field along the waveguide must be created in two directions perpendicular to each other, therefore, the field has a 90° phase difference in two perpendicular directions [30]. Due to the circularity, the fields are in the vertical and horizontal directions, degenerated, that is, with the same cutoff frequency. Bellow, its theory is presented [33]

$$\vec{E}_1 = E_m \cos(\omega t - kz)\, \hat{a}_y$$
$$\vec{E}_2 = E_m \cos\left(\omega t - kz - \frac{n\pi}{2}\right) \hat{a}_x \tag{6}$$

where n must be an odd integer. In the structure, to be able to have a CP TE_{11} mode instead of a linear TE_{11} mode, we need to create two electric currents in the vertical and horizontal direction, hence, they are at a quarter-guide wavelength distance from each other. Note, due to the vertical current being ahead of the horizontal, the type of circular polarization will be left-handed. To increase the CP TE_{11} mode purity, the inner is connected to the two opposite walls in horizontal and vertical directions. Note that the distance between the two cores must be at a half-guide wavelength distance from each other. Fig. 2 illustrates this issue schematically. In Fig. 2, $d = {}^{n\lambda_g}/_{4}$.

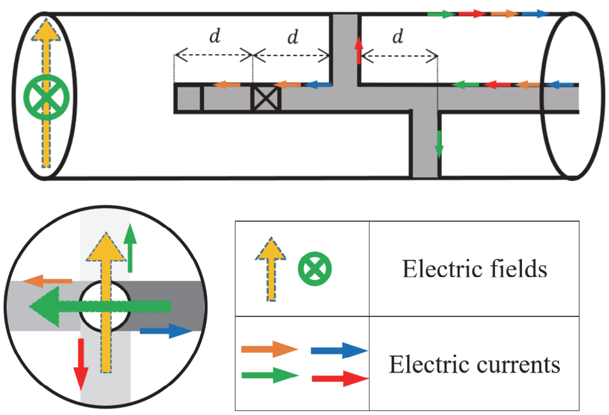


Fig. 2. Electric currents, magnetic and electric fields in the circular left-handed CPMCA

III. Design

The circular waveguide length is selected to be 50 mm. Due to an input impedance of 50 Ω (to minimize return losses if experimented [30] and [31]), according to (2), the internal conductor radius can be calculated as follows

$$a = be^{-\left(\frac{Z_0}{60}\right)} \tag{7}$$

i.e., $a \cong 21.7$ mm. The interspace formula of four body-connected inners can be as follows [32]

$$d = \frac{n\lambda_g}{4} = \frac{nc}{4f\sqrt{1-\left(\frac{f_c}{f}\right)^2}} \tag{8}$$

where $f_c = 1.758$ GHz. So $d = 7.6n$. Due to increasing the impedance matching, a guide wavelength is added to the interspace of four inners. So $n = 5$. To select the working frequency, the return loss, which is mainly due to the difference in impedance between the coaxial and circular waveguide parts, should be lower than the acceptable value. See Eq. (9)

$$S_{11} < -10dB \tag{9}$$

According to (5), and $\eta_{TEM} = \eta_0 = 377\ \Omega$, the maximum value of $Z_{TE_{11}}$ can be calculated, which is 94.93 Ω. Now, according to (10) and $Z_{TE_{11}}$ range, the range of the operating frequency must be $f > 2.068$ GHz. The working frequency is selected at 10 GHz. After the initial design, the dimensions were optimized by Microwave Studio CST software.

IV. Simulation and Optimization

The antenna was excited by a waveguide port. Due to the low-frequency bandwidth, a frequency solver has been used in it. Furthermore, to optimize, the connection angle of the inners to the body - which is the same angle for all inners - is optimized to achieve low return losses, SLLs, and an axial ratio close to zero decibels.

In Fig. 3, the simulated view of the CPMCA is shown.

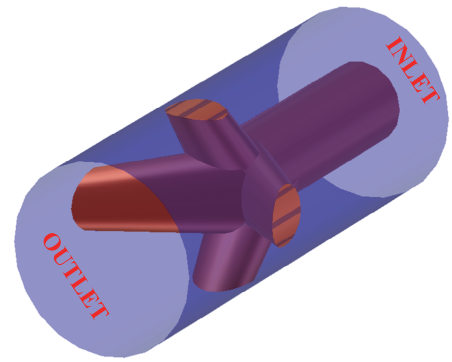


Fig. 3. Simulated view of left-handed CPMCA

The antenna body is so simple and consists of only like hollow cylinder. The length and diameter of the body are 125 and 50 mm, respectively. To increase the gain also, you can use a conical horn antenna. Of course, this article does not cover this conical horn. After optimization, the final dimensions are obtained and presented in Fig. 4.

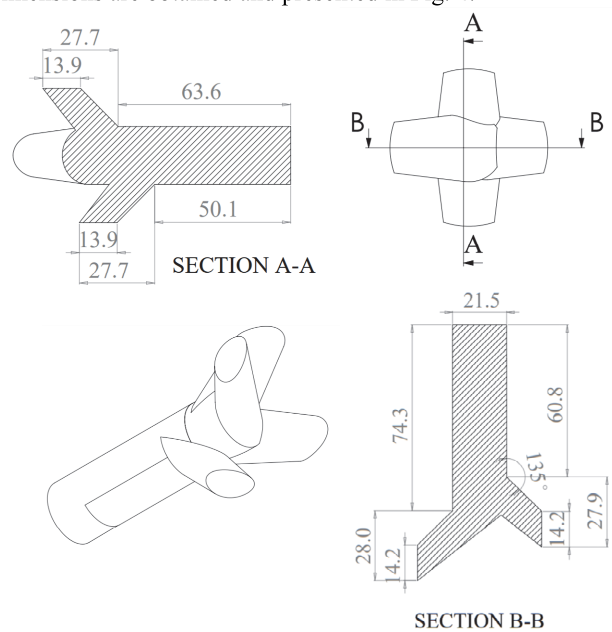


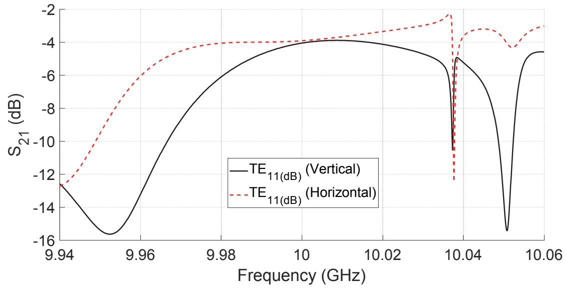
Fig. 4. Final dimensions of CPMCA

V. Results

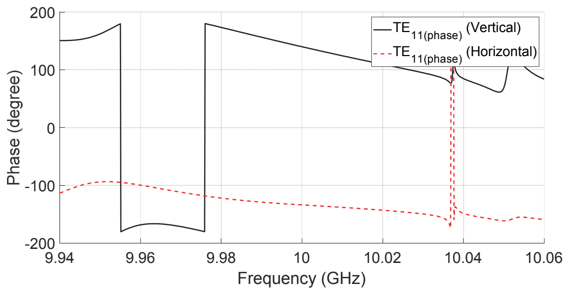
The consequence of any MCA consists of two categories, mode conversion result, and radiation. The mode conversion result consists of mode conversion efficiency, but the radiation results consist of the return loss, the gain radiation pattern, the beam-width, and the axial ratio.

A. Mode Conversion Result

As shown in Fig. 5, the magnitude of the vertical and horizontal TE_{11} modes are the same, at 10 GHz frequency. But it is not enough to have circular polarization. To have circular polarization, on the other hand, the phase difference of these two modes must be 90°.



a



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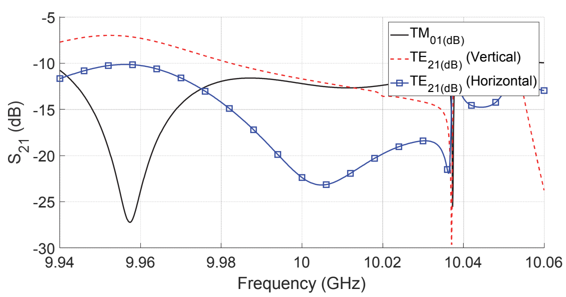

c

Fig. 5. The absolute and phase of the modes in the aperture: (a) the absolute and (b) phase of the S_{21} parameter of two main modes, and (c) the absolute of the three unwanted modes.

Note, to achieve the circular polarization, we create electric fields in two perpendicular directions with equal absolute (see Fig. 5(a) and a phase difference of 90° (see Fig. 5(b)). Hence, the phase difference between the vertical and horizontal TE_{11} modes must be 90°. Fig. 5(b) shows that the phases of the vertical and horizontal TE_{11} modes are 139.9° and −133.6°, respectively. By the fact that, we have,

$$\Delta\varphi_d = \left|360 - \left(139.9 - (-133.6)\right)\right| = 86.5\,° \qquad (10)$$

Only two modes, vertical and horizontal, should be excited at the antenna aperture, and the intensity of the higher modes should be negligible (see Fig. 5(c)).

B. Radiation Results

In Fig. 6, the sidelobe level (SLL) and main lobe deviation (MLD) of the CPMCA, in the horizontal ($\varphi = 0°$) and vertical ($\varphi = 90°$) planes, are shown. The results indicate that SLL is less than −11 dB and the deviations of the main lobes from the bore-sight are negligent.

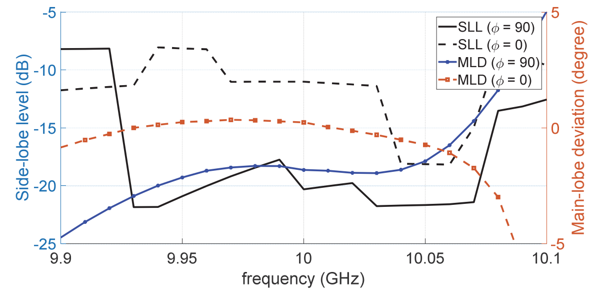

Fig. 5. The sidelobe level (SLL) and main lobe deviation of the CPMCA in the horizontal ($\varphi = 0°$) and vertical ($\varphi = 90°$) plane

In Fig. 7, the results of the return loss and the axial ratio of the CPMCA are indicated. The return loss is less than −16 dB, at the working frequency, which is very good. At the working frequency, the axial ratio is about 0.43 dB, which is much less than 3 dB.

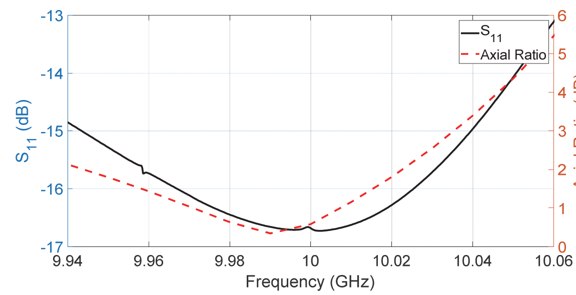

Fig. 6. The return loss and the axial ratio of the CPMCA in frequency

At 10 GHz frequency, the results of the axial ratio in degree, in two horizontal and vertical planes, are indicated in Fig. 8. According to Fig. 8, the axial ratio beamwidth is equal to 43°.

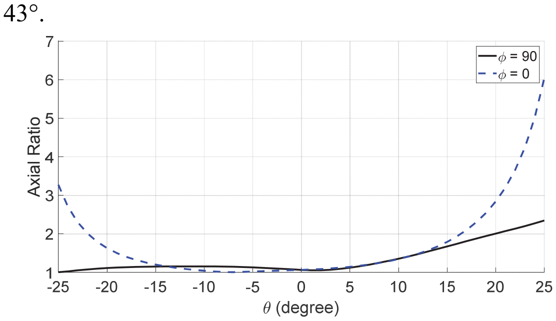

Fig. 8. The axial ratio in degree at 10 GHz frequency

Finally, in Fig. 9, the left-handed radiation patterns of the CPMCA at the working frequency are indicated.

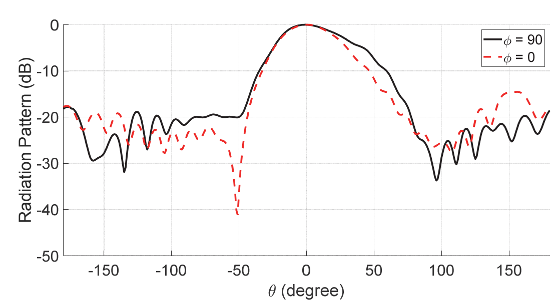

Fig. 9. The left-handed radiation patterns of the CPMCA gain at 10 GHz frequency, in the horizontal and vertical planes

TABLE 1
THE COMPARISON OF THIS CPMCA WITH THE PREVIOUS WORKS

Ref.	$\frac{\text{Length}}{\lambda}$	$\frac{\text{diameter}}{\lambda}$	Frequency [GHz]	High-power Capacity [MW]	AR at the center [dB]	AR 3dB beamwidth [degree]
This work	4.16	1.6	10	428	0.34	38
[22]	39.4	10.6	9.1	HPM*	Not provided	Not provided
[27]	4.8	4.1	4	600	0.8	23
[28] ‡	10	6	10	2000	Not provided	Not provided
[35] ‡	7.4	3.7	1.8	Not provided	Not provided	Not provided

*High-power microwave
‡ The structure is NOT a radiation system

C. *Power-Handling Capacity*

The power-handling capacity is an important feature of this work. Based on the proper design of the MCA, the possibility of the electrical breakdown is reduced and the power-handling of the antenna is increased. In Fig. 10, the simulated result of the electrical fields of the CPMCA is indicated.

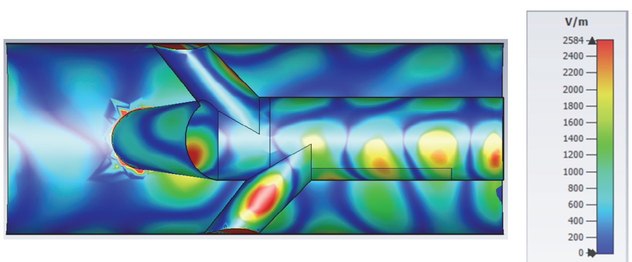

Fig. 10. The electrical fields of the CPMCA

The power-handling capacity can be calculated by

$$P_{Max} = P_{in}\left(\frac{E_{Max}}{E}\right)^2 \tag{11}$$

where P_{Max} is the power-handling capacity, P_{in} the input power and is equal to 0.5 W, here, E is the maximum E-field under P_{in} injection, and E_{Max} is the E-field breakdown threshold which can be calculated by Kilpatrick Guideline [34] and equal 75.6 MV/m, in vacuum. According to (11), the power-handling capacity of the CPMCA is 428 MW.

VI. MODE CONVERTERS COMPARISON

The previous MCAs are listed in Table 1, and compared with this work.

VII. CONCLUSION

In the article, an MCA with left-handed circular polarization is presented. CPMCA is designed and simulated at an arbitrary frequency, which is 10 GHz. The overall axial dimension of CPMCA is less than 150 mm. The input dimensions of CPMCA are designed for 50 Ω impedance to minimize return losses if tested. The sidelobe level in the horizontal and vertical planes is less than −11 dB, at the working frequency. In the work, the main lobe deviation from the bore-sight is negligent, in two perpendicular planes, at the working frequency. The S_{11} and axial ratios of CPMCA are about −16.5 dB and 0.43 dB, respectively. Also, the axial ratio is within the range of ±20° in the acceptable range. Due to the power-handling capacity being 428 MW, the CPMCA is suitable as an MCA of an HPM electromagnetic diode.

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