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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

DESIGN AND OPTIMIZATION OF A DUAL-BAND IRIS POLARIZER

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ABSTRACT

The structure that transforms a linear polarized signal into right-hand or left-hand circularly polarized signals is called a polarizer. In this study, a dual-band waveguide polarizer used in satellite communications is presented. The waveguide polarizer is designed using iris structures on a square waveguide. The purpose of the polarizer is to transmit the ±45° tilted linearly polarized signal at its input to the output as a right-hand or left-hand circularly polarized wave, and vice versa. At the input of the polarizer, a transition is designed between the WR42 waveguide and the square waveguide. At the output stage, a transition from square waveguide to circular waveguide is designed. In this paper, the design steps of both the polarizer and the transition sections, the optimization parameters, and simulation results are presented in full detail. The simulations are performed with a commercial electromagnetic simulation software, CST Studio Suite. The design operates within the Ka-band, specifically at 17.2 – 21.2 GHz and 27.5 – 31 GHz frequency bands. The insertion loss of the iris polarizer is <0.05 dB, the return loss is >23 dB, and the phase difference is less than 15° around 90° for both bands.

Keywords: Iris Polarizer, Dual-Band Polarizer, Ka-Band.

ÇİFT-BANT İRİS POLARİZÖR TASARIM VE OPTİMİZASYONU

ÖZ

Doğrusal polarizasyonlu bir sinyali sağ-el veya sol-el dairesel polarizasyonlu bir sinyale dönüştüren yapılar polarizör olarak adlandırılmaktadır. Bu çalışmada, uydu haberleşmesinde kullanılan çift-bant dalga kılavuzu polarizör tanıtılmıştır. Dalga kılavuzu polarizör, kare dalga kılavuzu üzerine iris yapıları kullanılarak tasarlanmıştır. Polarizörün amacı, girişine gelen ±45° yatık doğrusal polarizasyonlu sinyali çıkışına sağ-el ya da sol-el dairesel polarizasyona sahip dalga olarak iletmektir. Polarizörün girişinde WR42 dalga kılavuzu ile kare dalga kılavuzu arasında bir geçiş kısmı tasarlanmıştır. Çıkışında ise kare dalga kılavuzundan dairesel dalga kılavuzuna geçiş tasarlanmıştır. Bu dokümanda, polarizörün ve geçiş kısımlarının tasarım adımları, optimizasyon sonucunda elde edilen parametreler ve simülasyon sonuçları tüm ayrıntıları ile sunulmuştur. Simülasyonlar, ticari bir elektromanyetik simülasyon programı olan CST Studio Suite ile gerçekleştirilmiştir. Tasarım Ka bantta, 17.2 – 21.2 GHz ve 27.5 – 31 GHz frekans aralıklarında çalışmaktadır. İris polarizörün araya girme kaybı <0.05 dB, geri dönüş kaybı >23 dB ve faz farkı iki bant için de 90° etrafında 15°'den küçüktür.

Anahtar Kelimeler: *İris Polarizör, Çift Bant Polarizör, Ka Bant.*

1. INTRODUCTION

Antennas are structures that enable the propagation and receiving of electromagnetic waves. Antenna design depends on the polarization type of the wave and the field of application.

Antennas are inevitably used in satellite communications, where signal transmission by cable is impossible. Satellite communications is one of the most studied areas in space operations (Kolawole, 2002). The main purpose of a communication satellite is to assist in the transmission of information or messages from one point to another in space. The transmitted information can be audio, video, or digital data. This information can also be transmitted from the earth to the satellite or vice versa. The transmitted wave between the earth and the satellite passes through the ionosphere. As the wave passes through the ionosphere, the wave may rotate due to free electrons in the ionosphere, and the polarization direction of the wave may change. Since circularly polarized waves are not affected by polarization rotations in the ionosphere, they are preferred in satellite communications (Dondl, 1995). The device that is called a polarizer is used to convert a linearly polarized wave into a circularly polarized wave (or vice versa) (Kitsuregawa, 1990). There are different types of polarizers depending on the frequency and area of application. Septum polarizer, circular polarizer, corrugated polarizer, and iris polarizer are some of the most commonly used polarizers (Eom & Korchemkin, 2006) (Jazani & Pirhadi, 2018) (Tribak, Mediavilla, Cano, Boussouis, & Cepero, 2009) (Güvenç, Şişman, & Ergin, 2023). The structure of the iris polarizer is especially preferred in high-frequency applications. This polarizer performs polarization transformation with the irises in its structure (Chambelin & Pintos, 2006) (Tucholke, Arndt, & Wriedt, 1986).

In this study, a new polarizer is designed by adding irises on a square cross-section waveguide. At the input of the polarizer, a transition stage is designed between the WR42 waveguide and the square waveguide. At the output of the designed polarizer, a transition stage from square waveguide to circular waveguide is also designed. In the present study, it is assumed that the output of the polarizer will not be connected to a circular waveguide; it will radiate into free space serving as the feed to a reflector. Therefore, far-field simulations are carried out for the radiation pattern of the circularly polarized wave emanating from the polarizer.

Simulations are performed with a commercial electromagnetic simulation software, CST Studio Suite®. CST Studio Suite enables the solution of electromagnetic (EM) simulations using methods such as the Finite Element Method (FEM), Finite Integration Technique (FIT), and Transmission Line Matrix Method (TLM). Additional EM solvers for high-frequency applications of electrically large structures complement the general solvers. All EM solvers are based on solving Maxwell's equations by different methods. Time domain solvers use the Finite-Difference Time-Domain (FDTD) method to solve Maxwell's equations. Frequency domain solvers use the Finite Element Method (FEM) to solve Maxwell's equation. The two solvers use two different methods for the EM simulation solution of the same structure. Simulations of the iris polarizer structure are performed with the time domain solver and the frequency domain solver independently. Therefore, the results presented here are verified by different numerical analysis methods.

The design operates dual-band within the Ka-band; more specifically at 17.2 – 21.2 GHz and 27.5 – 31 GHz frequency bands. 17.2 – 21.2 GHz and 27.5 – 31 GHz are two bands that are commonly used in receiving and transmitting circuits, respectively. A structure designed for these two bands is expected to have high return loss (>20 dB), low insertion loss (<0.2 dB), and a phase difference close to 90°. The insertion loss of the iris polarizer is less than 0.05 dB, the return loss is greater than 23 dB, and the phase difference is less than 15° around 90° for both bands. The antenna directivity of the structure with only the circular waveguide (without basic or corrugated horn) is between 8.5 and 13 dB. The side-lobe level across the band is less than -20 dB.

In this study, the design steps of the structure including the transition stages added to the input and output are given in Section 2. Electrical results and far-field simulation results of the polarizer are presented in Section 3. Conclusions and evaluations are given in Section 4.

2. IRIS POLARIZER

2.1. The Polarizer Structure

The iris polarizer contains thin metals positioned on two opposite walls of the square waveguide. These thin metals are called irises. The irises on the polarizer are shown in Figure 1.

In Figure 1, the wave at the input of the iris polarizer is a 45° tilted linearly polarized wave. When this wave is analyzed as two orthogonal (vertical and horizontal) components, the vertical component travels through the polarizer while interacting with the irises whereas the horizontal component is not affected by the irises. In other words, the irises slow down the vertical component while the horizontal component propagates as if the waveguide had no irises. The iris designs are made so that the phase difference between the vertical component and the horizontal component is 90°. Thus, a circularly polarized signal is obtained at the polarizer output. Whether the circularly polarized signal is right-hand or left-hand depends on whether the wave at the input of the polarizer is tilted +45° or –45°, respectively. Note that the sign of the tilt angle can be controlled by the direction of the TE_{01} component.

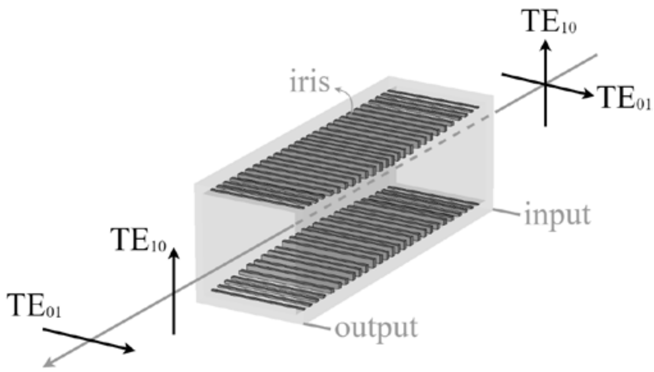

Figure 1. *The structure of the iris polarizer and polarizations at the input and output.*

2.1. Polarizer Design

Iris polarizer design consists of the design of two components: the square waveguide and irises. The square waveguide dimensions are calculated depending on the frequency band. For a rectangular waveguide, the dimensions are calculated depending on the cut-off frequency (Pozar, 2004):

$$f_{c,mn} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (1)$$

where $f_{c,mn}$ is the cut-off frequency, m and n are the modes, a and b are the dimensions of the waveguide. m and n can have values 0,1,2,3... . For a square waveguide $a = b$. For TE_{10} and TE_{01} modes, mn is calculated by taking 10 or 01. For 17.2-21.2 GHz and 27.5-31 GHz frequency bands, the cut-off frequency is 13 GHz. In this design, the size of the square waveguide is calculated as 11.75 mm. With this size, the next higher-order mode is TE11 with a cut-off frequency of 37.46 GHz. Since the design operates in dual-band, the size of the waveguide is selected larger than the standard waveguide. The size of the iris is of great importance for achieving return loss, low insertion loss, and a phase difference close to 90° in dual-band. In this design, the number of irises, thickness, height, width, and spacing between irises are calculated. Then the structure is fine-tuned to improve its performance in dual band. The thickness of the iris, *t*, the space between the irises, *g*, the iris height, *h*, and the number of irises are other design parameters. Figure 2 shows the iris parameters on the polarizer.

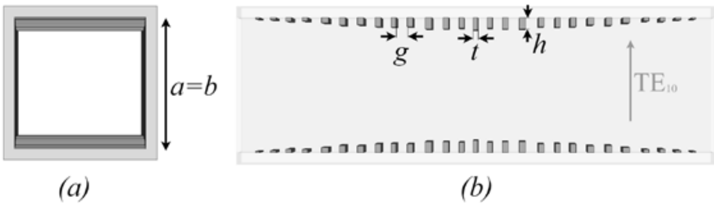

Figure 2. *Geometry of iris polarizer (a) front view, (b) side view.*

For the phase difference between the vertical and horizontal components of the linearly polarized wave at the input of the polarizer to be 90° at the output, the vertical component has to be delayed by the extra path provided by the irises. Therefore, each of the iris parameters is of great importance to provide the phase difference. While achieving this goal, the return loss must be low and the signal transmission must be high. Iris thickness (t) is the parameter that directly affects the phase difference. In the design, the initial value of each iris thickness is calculated as follows (Hwang & Lee, 2014):

$$t = 0.15\lambda_m \tag{2}$$

where λ_m is the guided wavelength at the center frequency. Optimization is performed to fine-tune the phase difference in dual-band applications. As a result of the optimization, the iris thicknesses in the design vary between $0.34 - 0.6$ mm. The gap between the irises is also a parameter that directly affects the phase difference. The best electrical results are obtained when the gap next to each iris is at least twice the thickness of the iris:

$$g > 2t \tag{3}$$

As a result of the optimization, the iris gaps in the design vary between $0.82-1.63$ mm. Another important design parameter is the height of each iris. The iris height significantly affects the phase difference as well as the return loss. Considering the polarizer structure, the height of the iris increases from one end to the center of the polarizer and decreases symmetrically from the center of the polarizer to the other end. Since the return loss is inversely proportional to the height of the front iris, using this configuration increases the return loss by decreasing the height of the front iris. The following range is used for iris heights:

$$h = (0.01 - 0.1)\lambda_m \tag{4}$$

As a result of the optimization, the iris heights in the design vary between $0.12-1.06$ mm. The number of irises in the polarizer also affects the phase difference. The number of irises can be increased so that the output phase difference between the wave components is close to 90° throughout the desired band. The number of irises can be odd or even (Hwang & Lee, 2014). This study is initially designed with 23 irises. However, 23 irises are not enough for a phase difference close to 90° in dual-band. As a result of the simulations, the number of irises is increased to 27.

Table 1. *Dimensions of the irises after optimization.*

Parameter	**Dimension (mm)**	**Parameter**	**Dimension (mm)**	**Parameter**	**Dimension (mm)**
t_0	0.41	g_0	0.	h_0	1.06
t_1	0.44	g_1	0.82	h_1	0.91
t_2	0.49	g_2	0.88	h_2	0.96
t_3	0.55	g_3	0.98	h_3	0.98
t_4	0.49	g_4	1.1	h_4	0.78
t_5	0.44	g_5	0.98	h_5	0.82
t_6	0.51	g_6	0.88	h_6	0.77
t_7	0.53	g_7	1.02	h_7	0.61
t_8	0.49	g_8	1.06	h_8	0.65
t_9	0.6	g_9	0.98	h_9	0.45
t_{10}	0.48	g_{10}	1.2	h_{10}	0.28
t_{11}	0.45	g_{11}	0.96	h_{11}	0.30
t_{12}	0.48	g_{12}	0.9	h_{12}	0.28
t_{13}	0.34	g_{13}	0.96	h_{13}	0.12

The irises on the two opposite walls of the polarizer are symmetrically designed. There is one iris in the center of the wall of the polarizer and 13 symmetrical irises on either side of the center iris. The iris in the center is called the 0th iris. The iris numbers continue to increase from the center to the end of the polarizer. The final values of t, g, and h for each iris are given in Table 1.

2.2. The Transition Sections

The iris polarizer is designed to be used in the feed structure of an antenna system. Therefore, a circular transition is designed at the output of the polarizer which supports circular polarization. The circular waveguide can be used as a feed by adding a basic or corrugated horn aperture. The radius r of the circular waveguide is calculated for the cut-off frequency $f_{c,mn}$ by the equation (Pozar, 2004):

$$f_{c,mn} = \frac{p'_{nm}}{2\pi r\sqrt{\mu\varepsilon}} \tag{5}$$

where nm indicates the mode and p'_{nm} value is 3.83 for TE_{01} mode. In this design, the radius of the circular waveguide is determined as 7 mm as a result of calculations and simulations. The cut-off frequency for the next higher mode (TE_{11}) is calculated to be 37.46 GHz. A loft structure is used between the circular waveguide and the square polarizer. The circular transition structure is shown in Figure 3. As a result of the simulations, the length of the loft structure and the waveguide are 12 mm and 10 mm respectively.

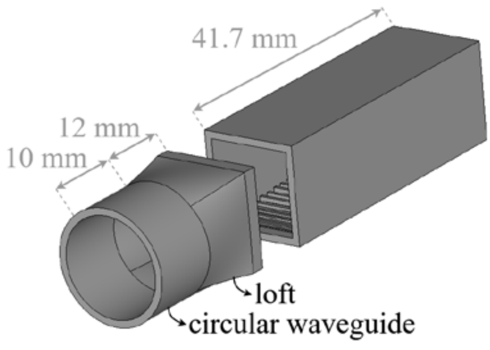

Figure 3. *Iris polarizer and circular transition.*

The input of the polarizer is a square waveguide and does not conform to standard waveguide dimensions. A transition is used to convert this input to standard dimensions. One end of the rectangular transition is a square waveguide, and the other end is a WR42 waveguide with a loft structure between them. The WR42 waveguide is designed at an angle of 45° to the vertical so that the wave arrives tilted at ±45° to the input of the polarizer. Therefore, TE_{10} mode from WR42 is converted as RHCP wave to the other end of the polarizer, while TE_{01} mode is converted as LHCP wave. Figure 4 shows the polarizer and transition sections. As a result of the simulations, the length of the loft structure and the waveguide are determined as 20 mm and 10 mm, respectively.

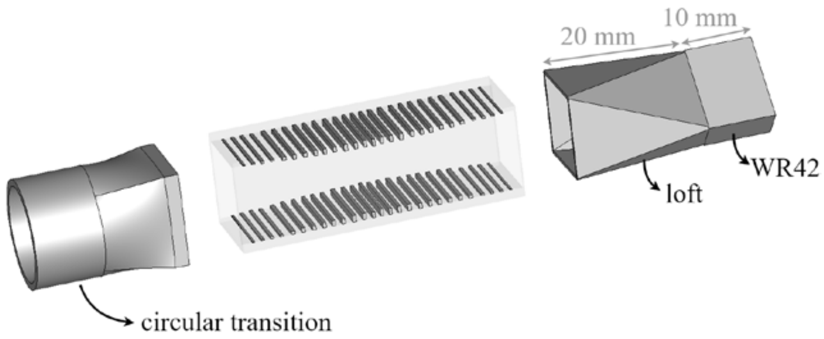

Figure 4. *Iris polarizer and transition sections.*

3. SIMULATIONS

The analysis and simulations of the dual-band (17.2-21.2 GHz and 27.5-31 GHz) polarizer and transition sections are carried out with the commercial electromagnetic simulation software, CST Studio Suite. The analyses are carried out in two steps. In the first step, the S parameters are calculated *for each mode* from the WR42 input (port 1) to the end of the square polarizer section (port 2). The circular transition is not included in this first analysis because the output from the circular section is not intended as a waveguide port; it is rather conceived as the feed aperture for the reflector antenna. Therefore, in the second part of the analysis, the whole structure including the circular transition section is analyzed as an antenna with a single port, and its radiation characteristics are studied.

Hence, firstly, the performance of the polarizer and the rectangular transition is analyzed. On the polarizer, 27 irises are used on each wall. A rectangular transition section is used to ensure that the signal arrives at ±45° to the iris input. The rectangular waveguide is defined as port 1 and the output of the polarizer is defined as port 2. The reflection and transmission coefficients between the two modes at port 1 and the two modes at port 2 are analyzed. The return loss and insertion loss of the structure are given in Figure 5. The two bands of interest are marked with green in both figures. It is seen that the return loss is greater than 30 dB from 17.7 to 21.2 GHz, but the return loss is 23 dB from 27.5 to 31 GHz. Better return loss values are achieved in port 1 where the waveguide transition section exists. In port 2, there is no transition section. Therefore, the irises stand close to the port and there is not much space for the evanescent modes to fade away. Hence, a higher S22 is not surprising and better performance is expected in the presence of the circular transition section. The transmission between the ports is also very well with an insertion loss less than 0.05 dB throughout the two bands. Note that the S21 values are given separately for both modes. This is important because each mode (vertical and horizontal) experience different electrical paths and although even if the phase difference between them turns out to be 90° a difference between the insertion losses will mean deviation from circular polarization. With this perspective, the largest difference of 0.035 dB between the two modes causes only 0.8% deviation in the axial ratio of the circular polarization which is more than acceptable.

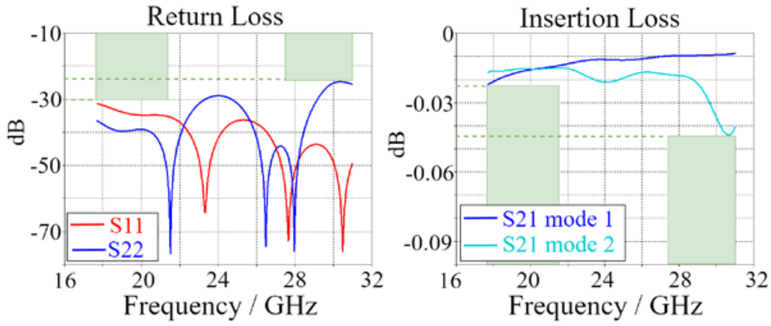

Figure 5. *Return and insertion losses for the polarizer and rectangular transition.*

The phase difference between the vertical component and the horizontal component of the wave should be approximately 90° at the end of the polarizer. In dual-band structures, it is difficult to set the phase difference to 90° throughout the operation bands. The initial goal of the present study was to achieve a phase deviation of 15°. The phase difference of the resulting structure is given in Figure 6. It is seen that the phase-difference along both bands is tuned around 90° the goal of 15° deviation is achieved with values ranging between 83° and 98°.

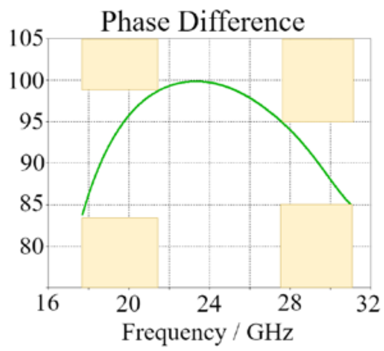

Figure 6. *Phase difference between the vertical and horizontal wave components at the output.*

The performance results of the iris polarizer are also presented in Table 2. The electrical performances of this study and other polarizer studies in close frequency bands are compared in Table 3. Note that although the literature values for the return loss and phase difference are better, the present study covers a much larger frequency range (f_{max} / f_{min} = 31/17.7 = 1.75) compared to <1.53 in the literature.

Table 2. *Electrical performance of the iris polarizer and rectangular transition.*

Frequency (GHz)	**Minimum Return Loss (dB)**	**Phase Difference Range (°)**
17.7 – 21.2	30	83 – 98
27.5 – 31	23	85 – 95

Table 3. *Comparison of the electrical performance.*

	Frequency (GHz)	**Minimum Return Loss (dB)**	**Phase Difference Range (°)**
This Study	17.2 – 21.2 27.5 – 31	23	83 – 98
(Hwang & Lee, 2014)	20.8 – 21.2 30.6 – 31	30	86 – 90
(Leal-Sevillano, Ruiz-Cruz, Montejo-Garai, & Rebollar, 2013)	19.75 – 20.25 29.75 – 30.25	27	89 – 91
(Liu, Li, Li, & He, 2008)	24 – 36	27	82 – 98

In the second stage of the analysis, the circular waveguide transition section at the output of the iris polarizer structure is included. Far-field (antenna) simulation results of the structure are analyzed. The return loss of the structure is seen to be greater than 32 dB in Figure 7. A return loss higher than 32 dB means that 99.937% of the energy that enters the polarizer is radiated into the free space through the circular end, which is a very good figure of efficiency. The far-field pattern is shown in Figure 8. The rotational symmetry of the radiation pattern indicates that the axial ratio of the electric field at the aperture is around unity. The side-lobe value of the structure over the entire frequency band is around -20 dB.

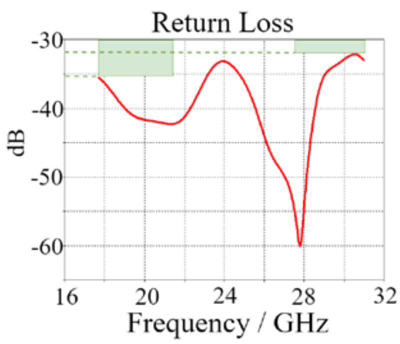

Figure 7. *Return loss of all structure.*

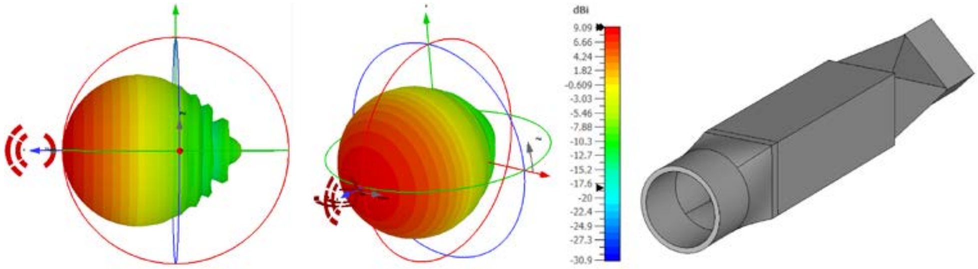

Figure 8. *Far-field pattern of the iris polarizer and transitions.*

Figure 9 shows the electric field distribution of the structure consisting of the iris polarizer and the circular waveguide. From the input of the iris polarizer to the end of the circular waveguide, the signal changes from linearly polarized to circularly polarized.

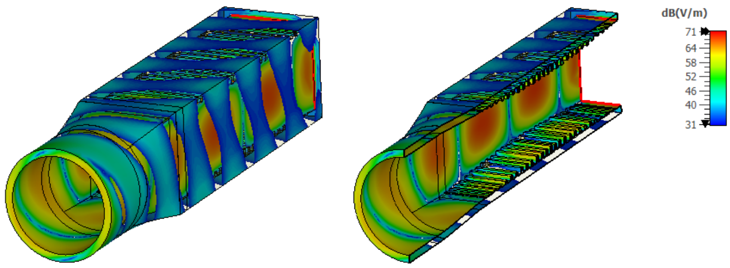

Figure 9. *Simulated electric field distribution of the iris polarizer and circular waveguide*

The directivity and realized gain of the structure over the full frequency band are given in Figure 10. The gain is above 8.5 dB which is satisfactory for the dish that the polarizer is intended to feed.

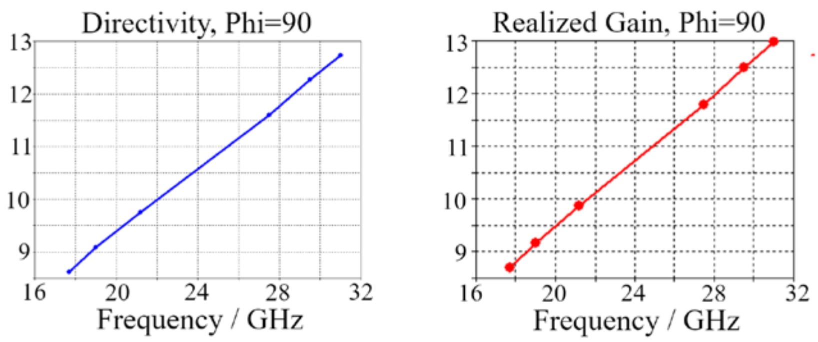

Figure 10. *Directivity (dBi) and realized gain (dBi) of the design for all frequency ranges.*

4. CONCLUSION

In this paper, the design and optimization results of a dual-band iris polarizer with transition sections are presented. The design works within the Ka-band, specifically at the 17.2 – 21.2 GHz and 27.5 – 31 GHz frequency bands. The iris polarizer structure consists of 27×2 irises on two opposite walls on the square waveguide. The irises create a delay on the vertical component of the ±45° tilted linearly polarized signal at the input of the polarizer. Thus, the signal arrives at the end of the polarizer as either a RHCP or LHCP wave. WR42 to square transition is added to the input of the polarizer. At the output of the polarizer, a transition from square waveguide to circular waveguide is designed. The insertion loss of the iris polarizer is <0.05 dB, the return loss is >23 dB, and the phase difference variation between the two linear components of the output wave is less than 15° around 90° for both bands. Far-field results are obtained with a circular aperture at the output of the polarizer structure. Directivity increases linearly with increasing frequency and the side lobe levels are around -20 dB.

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