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Fabrication of Low-weight Broadband 90º Waveguide Twist at X-Ku Band with 3D Printing Technology

Abdullah GENÇ[1], Habib DOGAN[2], İbrahim Bahadır BASYİĞİT[3], Selçuk HELHEL[4]

[1] Isparta University of Applied Science/Dep. of Mechatronics Engineering, Isparta, Turkey
abdullahgenc@isparta.edu.tr

[2] Ministry of Environment and Urbanization / Dept. of Building Inspection, Isparta, Turkey
habibdogan@gmail.com

[3] Isparta University of Applied Science/Dep. of Electrical-Electronics Engineering, Isparta, Turkey
bahadirbasyigit@isparta.edu.tr

[4] Akdeniz University/Dep. of Electrical and Electronics Engineering, Antalya, Turkey
selcukhelhel@akdeniz.edu.tr

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ABSTRACT

In this study, fabrication of low-weight broadband 90º waveguide twist at X-Ku band with 3D printing technology is proposed. Waveguide twist components are microwave components used to change the polarization direction of the electric field of the waveguides to 90º and it is also possible to change the polarization direction at the desired angle. Firstly, WR-75 rectangular waveguide is designed for TE_{10} dominant mode and fabrication of the component is made fused deposition modelling (FDM) technique with ABS thermoplastic coated with a total of 20 ±%10 µm copper plating. Simulation and measurement results for E-field, return losses and insertion losses are obtained at 10-15GHz. CST Microwave Studio is used as a simulation program. The S-parameters of the waveguide twist is compared with the rectangular waveguide with equal length. The performance of the broadband 90º waveguide twist component is examined depending on the length vary between 0.5λ and 4λ. By means of this 3D printing method, it is possible to fabricate passive microwave components are 80% cheaper and 90% lighter than commercial counterparts.

1. INTRODUCTION

The production of microwave passive components by additive manufacturing methods (AM) is widely preferred for reasons such as low cost, low weight and fast production [1]. Fused Deposition Modeling (FDM) that is one of the additive manufacturing methods is a good alternative to traditional production methods [2]. In this technique, thermoplastics are used since the internal structure of heat-induced thermoplastics does not deteriorate in solid-liquid state conversions. This

technology was developed by S. Scott Crump in the late 1980s and commercialized in 1990 [3]. The working principle is to form a layer by injecting the molten filament nozzle into a platform. Before applying the next layer, the thermoplastic material in the first layer hardens and in this way the desired 3D structure is obtained by the cross-sectional model. Thermoplastics such as ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid) are generally used, but ABS is preferred in applications where copper plating is required [4]. After forming the frame of the structure via a 3D printer, the metal coating is applied to all surfaces of the component. In order to make the surfaces of the component conductive, first electroplating and then electroless plating is performed. In order to achieve good performance, the component must have low surface roughness and high precision in the dimensions, especially at high frequencies [5].

Waveguide twist (WGT) components are microwave components used to change the polarization direction of the electric field of the waveguides to 90º and it is also possible to change the polarization direction at the desired angle [6]. There are many publications in the literature that contain different twist configurations and geometries [7-8]. WGTs with a continuous rotation are preferred in some applications, while rigid waveguide is preferred for integrated applications. Because the twist with rigid waveguide has a smaller volume than the other [9].

In this study, fabrication of low-weight broadband 90º WGT at X-Ku band with 3D printing technology is proposed. Firstly, WR-75 rectangular waveguide (RWG) is designed for TE_{10} dominant mode and fabrication of the component is made fused deposition modelling (FDM) technique with ABS thermoplastic coated with a total of 20 ±%10 μm copper plating. Simulation and measurement results for E-field, return losses and insertion losses are obtained at 10-15GHz. The S-parameters of the WGT is compared with the RWG with equal length. This study is organized as follows: Section 1 consists of the introduction and Section 2 consists of the design and manufacturing stages of the components. In Section 3, simulation and measurement results are obtained and interpreted. Section 4 consists of the result section.

2. DESIGN AND FABRICATION OF 90º WAVEGUIDE TWIST

In order to fabricate the 90º WGT, a RWG that has an equal length with the twist is firstly designed. For this purpose, the WR-75 RWG is preferred in the X-Ku band (10-15GHz). In TE_{10} dominant mode, cutoff frequency, f_c is determined as 7.886GHz and the dimensions of the RWG are calculated according to Equation 1. The operating frequency of that varies in the range of $1.25\ f_c < f < 1.89\ f_c$.

$$(f_c)_{mn} = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \quad (1)$$

where *m*, *n* are possible modes of EM wave and *a* and *b* are the dimensions of that. Theoretically, for the WR-75 RWG, approximately 0.1dB/m attenuation occurs at 10GHz. While the waveguides have air inside, different dielectric materials may also be used in some applications. As can be seen from Equation 1, the dimensions of the waveguide decrease due to the increase of the dielectric constant ε, while the dielectric losses increase due to the increase of the loss tangent, tanδ [10-11]. Therefore, in exclusive microwave applications, materials with high dielectric constant and low loss tangent are selected, but their costs are relatively very high. A standard UDR 120 flange is added to each component to connect the components to the VNA thanks to the guide-coaxial adapter. Profile views of a 100mm RWG, a flange, and a 100mm WGT are given in Figure 1. Also, the dimensions of the designed passive components are given in Table 1.

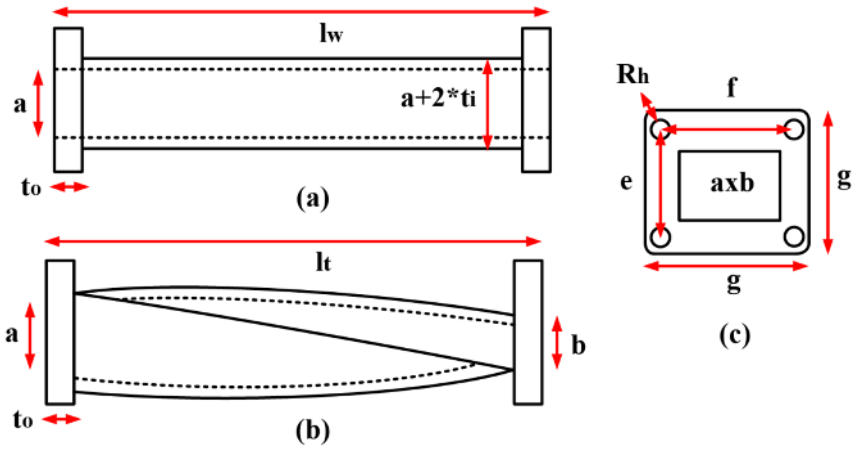


Figure 1: Profile views of (a) RWG (b) flange and (c) WGT components

Table 1 Parameters of the passive components

Components (mm)	*a*	*b*	*lw*	*lt*	*ti*	*to*	*Rh*	*f*	*e*	*g*
RWG	19.05	9.52	100	-	2	4	-	-	-	-
WGT	19.05	9.52	-	100	2	4	-	-	-	-
Flange	19.05	9.52	-	-	-	4	2.2	26.42	28.5	38.3

3. SIMULATION AND MEASUREMENT RESULTS

All simulations have been performed with the CST Studio Suite®, a full-electromagnetic simulation program that computes with the Finite Integration Technique (FIT). The number of meshes per wavelength is 20, the mesh shape is hexahedron and the boundary conditions in all directions is $\vec{E}_t = 0$. In the simulation, lossy copper (copper, annealed) having 5.8×10^7(S/m) electrical conductivity is used as a conductor and waveguide port is selected as the feed.

The measurement setup is given in Figure 2. The measurements were carried out in the laboratory of EMC Electronics in Gebze. S-parameters are measured by E8363B model Agilent PNA Microwave vector network analyzer (VNA) operating in 10MHz - 40GHz band. Also, PE9819 Pasternack waveguide-coaxial adapter compatible with WR-75 DK is used for connection between coaxial cable and waveguide. The maximum VSWR level of the adapter is 1.3: 1 and its maximum input power is 2.5Watts.

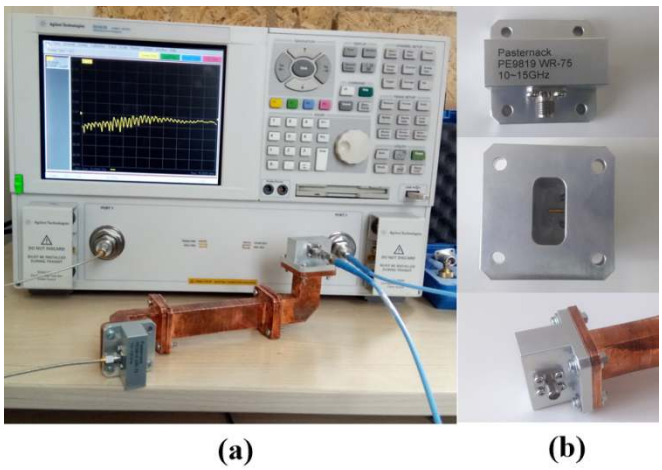


Figure 2: (a) Measurement setup with E8363B Agilent PNA Microwave vector network analyzer (b) PE9819 Pasternack waveguide-coaxial adapter

3.1. Performance of the RWG

There are two types of loss in the uniform *l*-length waveguide: reflection and ohmic losses and the total power attenuation α_T is given in Equation 2.

$$\alpha_T = \alpha_R + l\,\alpha_D \tag{2}$$

where α_R is the reflection losses due to the impedance mismatch in the flanges, and α_D is the ohmic losses caused by the metal walls inside the waveguide and are detailed in Equation 3 [12].

$$\alpha_R = -10\,\log(1 - |S_{11}|^2) \tag{3a}$$

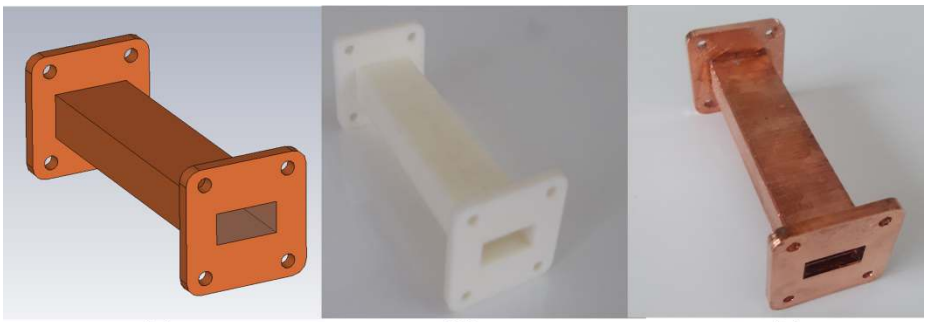
$$\alpha_D = -\frac{10}{l}\log\left(\frac{|S_{21}|^2}{1-|S_{11}|^2}\right) \tag{3b}$$

Ohmic losses are expressed in unit length as expected and are user-independent. The performances of the microwave passive components are determined according to the return loss as low as possible and the insertion loss as high as possible and given in Equation 4 respectively. Return loss can be expressed as the ratio of the energy supplied from the input port of the component to the energy reflected back to the input.

$$\text{Return loss} = -20\log|S_{11}| \tag{4a}$$

$$\text{Insertion loss} = -20\log|S_{21}| \tag{4b}$$

The photos of the proposed RWG with CAD model, 3D printed thermoplastic and copper-coated one is given in Figure 3.



(a) (b) (c)

Figure 3: The view of the RWG (a) CST model (b) 3D printed thermoplastic (c) copper-coated

Return loss, insertion loss and ohmic attenuation of the RWG are given in Figure 4. Accordingly, the ohmic (dissipative) attenuation versus frequency is calculated using Equation 5b. The return loss is less than -20dB in the whole frequency band and there is a difference of approximately 25dB between measured and simulated results. The maximum VSWR of the commercial Pasternack RWG is 1.04 (the level of return loss = 34.15dB) that is shown below by a blue line. The conduction loss of the component is close to 0dB for simulation and roughly -6dB for measurement. Simulation results are much better than measurement results due to the surface

roughness of components and defects in production as in the literature [13]. The ohmic attenuation is roughly 0.2dB/m and is higher in the low-frequency region.

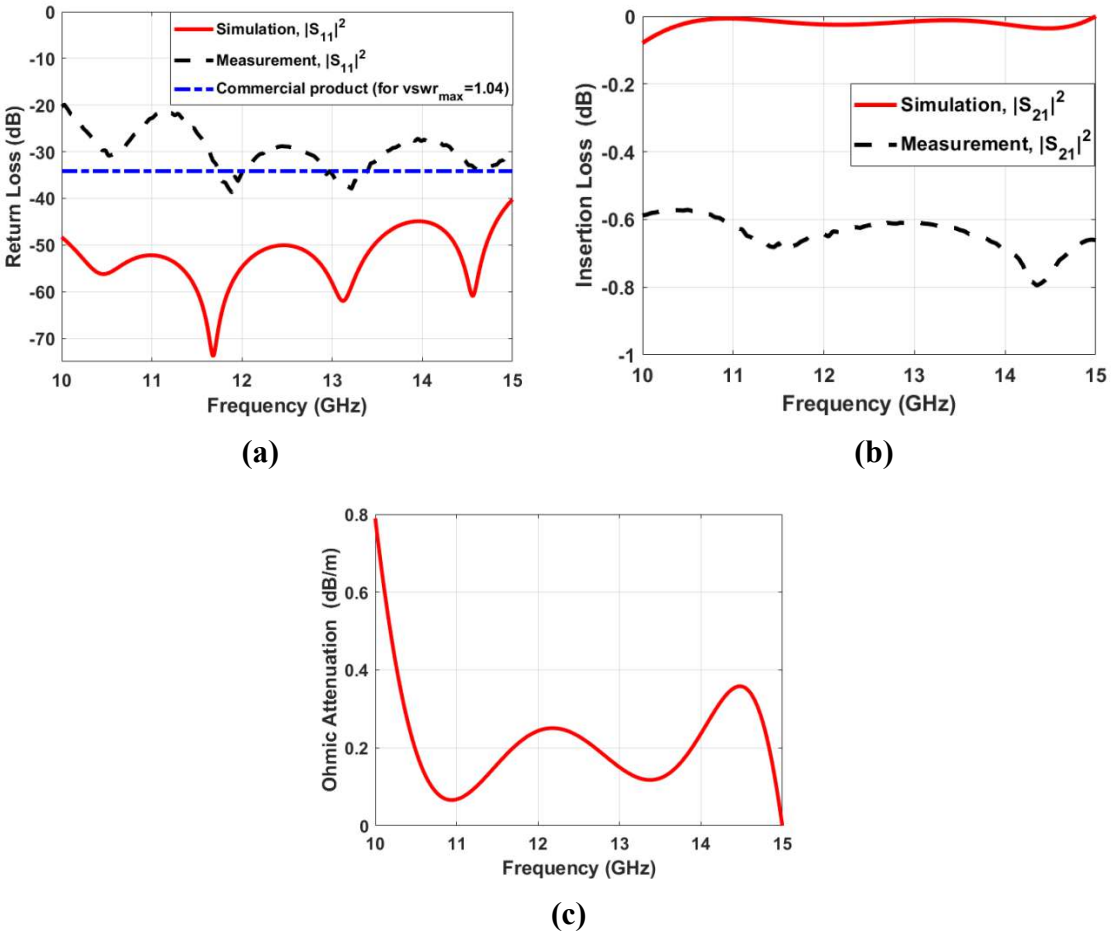


Figure 4: (a) Return loss (b) insertion loss and (c) ohmic attenuation of the RWG

3.2. Performance of 90º WGT

The photos of proposed WGT with CAD model, 3D printed thermoplastic and copper-coated one is given in Figure 5.

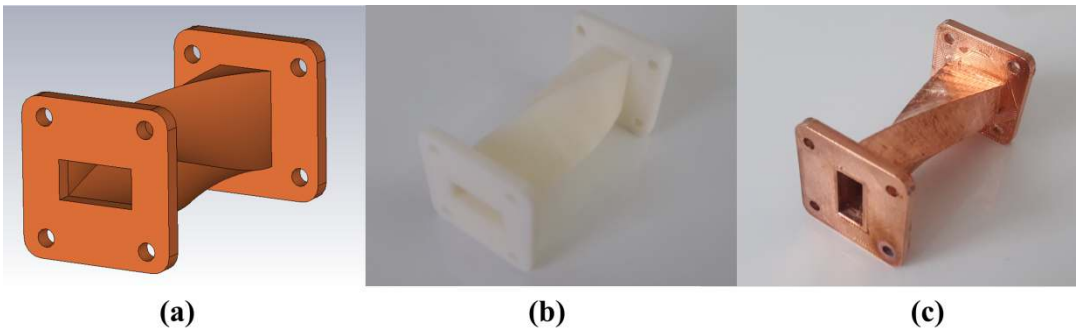


Figure 5: The view of the WGT (a) CST model (b) 3D printed thermoplastic (c) copper-coated

Return loss and insertion loss of the WGT are given in Figure 6. Accordingly, the return loss is less than -10 dB in the entire frequency range and there is a difference of approximately 30 dB between measured and simulated results. The maximum VSWR of PE-W28TW1001 model Pasternack WGT made of brass is 1.07 (the level of return loss = 29.42dB) that is shown below by a

blue line and the performance of the proposed component is very close to that of the commercial product. The transmission loss of the component is -0.15dB for simulation and roughly -7dB for measurement.

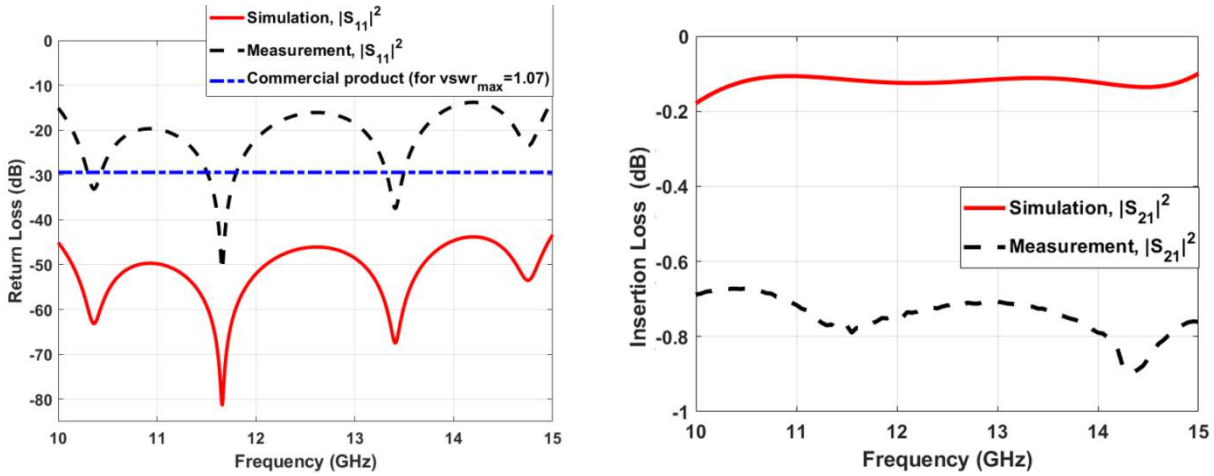


Figure 6: (a) Return loss and (b) insertion loss of the WGT

E-field distributions of the RWG and the WGT for 12GHz are given in Figure 7. Accordingly, the maximum electric field values of the RWG and the WGT in the simulation were 2310V/m and 2510V/m, respectively. Since the lengths of each passive microwave component are equal, the total number of waves is 6.5.

Comparison of return losses of the WGT depending on its length is given in Figure 8. In order to understand the effect of the component's length that varies between 0.5λ and 4λ on its performance, return loss values are compared. According to this result, if the length of WGT is increased to 4 wavelengths, its performance improves. However, there is no significant improvement in the performance for lengths longer than 4 wavelengths.

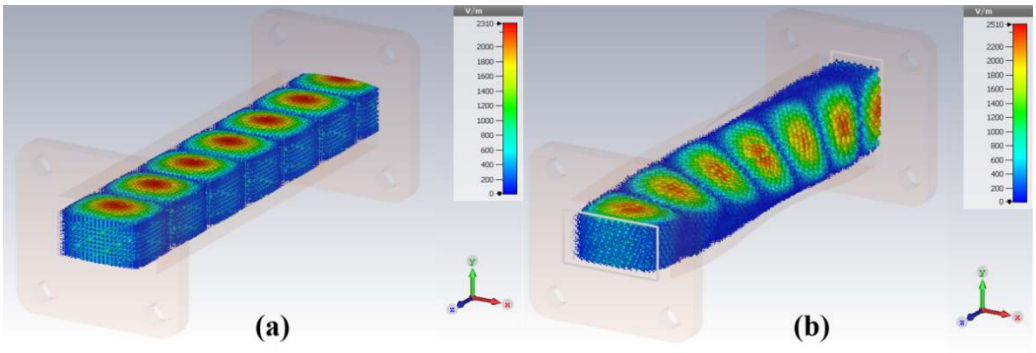


Figure 7: E-field distributions of (a) the RWG and (b) the WGT

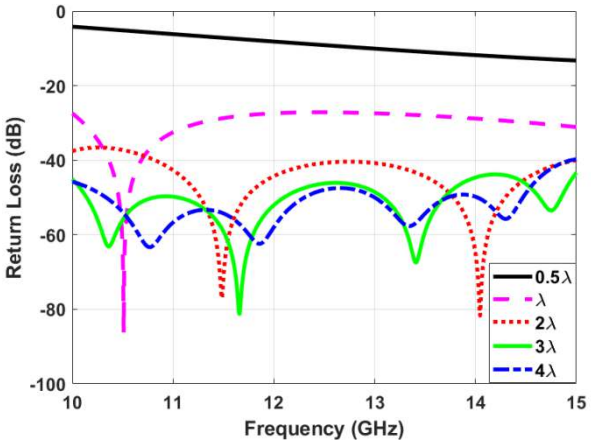


Figure 8: Comparison of return losses of the WGT depending on its length

4. CONCLUSION

Fabrication of Low-weight Broadband 90º WGT and RWG at X-Ku Band with 3D Printing Technology is proposed. By means of this 3D printing method, it is possible to fabricate passive microwave components are 80% cheaper and 90% lighter than commercial counterparts. For the the RWG, return loss is less than -20dB in all frequency range and there is a difference of ~25dB between the measured and simulated results. But for WGT, return loss is less than -10dB in all frequency range and there is a difference of ~30dB between the measured and simulated results. In addition, the performance of the broadband 90º WGT is examined depending on the length vary between 0.5λ and 4λ.

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