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Research Article

A 60 GHz Planar Diplexer Based on Substrate Integrated Waveguide Technology

Nikolaos Athanasopoulos, Dimitrios Makris, and Konstantinos Voudouris

Wireless Communications and e-Applications Research Group, Technological Educational Institute of Athens, Agion Spyridonos and Pallikaridi Street, 12210 Athens, Greece

Correspondence should be addressed to Nikolaos Athanasopoulos; nikathanaso@gmail.com

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This paper presents a millimeter-wave, 60 GHz frequency band planar diplexer based on substrate integrated waveguide (SIW) technology. Diplexer consists of a pair of 5th-order SIW bandpass channel filters with center frequencies at 59.8 GHz and 62.2 GHz providing 1.67% and 1.6% relative bandwidths, respectively. SIW-to-microstrip transitions at diplexer ports enable integration in a millimeter-wave transceiver front end. Measurements are in good agreement with electromagnetic simulation, reporting very good channel isolation, small return losses, and moderate insertion losses in the passbands. The proposed SIW planar diplexer is integrated into a millimeter-wave transceiver front end for 60 GHz point-to-point multigigabit wireless backhaul applications, providing high isolation between transmit and receive channels.

1. Introduction

The deployment of millimeter-wave integration technologies is critical for the wireless systems evolution. A variety of applications have been recently proposed in the frequency range between 60 GHz and 94 GHz including wireless networks [1], automotive radars [2], imaging sensors [3], and biomedical devices [4]. These systems require cost-effective technologies suitable for mass production and high density integration techniques, combined with a low-cost fabrication process. Substrate Integrated Waveguide (SIW) technology [5–8] is a promising candidate for providing compact, flexible, and cost-effective millimeter-wave circuits and systems which preserve most of the advantages of the conventional metallic waveguides, namely, complete shielding, low loss, high-quality factor, and high power handling capability [9]. Most of the classical passive components have been implemented in SIW technology. This solution usually permits to obtain components with a substantial reduction in size; moreover, the losses are lower than in the corresponding microstrip devices especially in the millimeter-wave frequency range, and there are no radiation and packaging problems. In the literature, SIW filters have received a particular attention. Focusing on the 60 GHz frequency band, in [10] a four-pole 60 GHz SIW bandpass filter has been modeled, while in [11] a 60 GHz SIW quasi-elliptic filter has been designed and fabricated.

The diplexer is one of the key components in a transceiver front end and greatly affects system's performance acting as channel separator. This becomes evident in the frequency division duplex systems where frequency separation between transmit and receive chains needs to be provided. Diplexer design is usually based on waveguide technology with excellent performance in terms of insertion loss and channel-to-channel isolation [12–14]. However, the design suffers from disadvantages such as being bulky, costly, and difficult to fabricate. Moreover, it cannot be integrated with the rest of the millimeter-wave planar integrated circuits that the transceiver front end consists of. On the other hand, diplexer implementation in SIW provides a compact, cost-effective solution preserving most of the advantages of the conventional metallic waveguides, while in parallel it enables the diplexer integration with the rest of the millimeter-wave transceiver front-end components. In the literature, SIW planar diplexers operating at 5 GHz and 25 GHz have been proposed in [15, 16], respectively, while the generalized

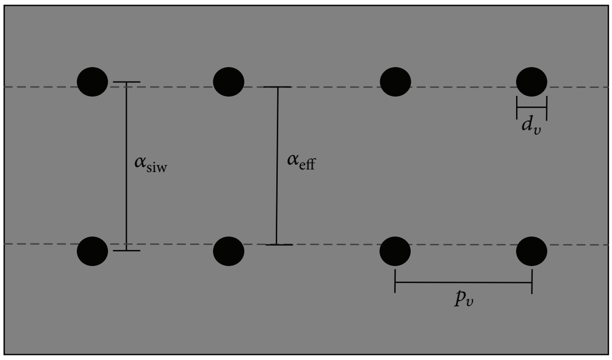

Figure 1: The SIW general structure.

1 GHz frequency band chebyshev SIW diplexer has been described in [17]. In [18] a 5 GHz frequency band SIW diplexer loaded by complementary split-ring resonators has also been proposed.

This paper is focused on a 60 GHz frequency band SIW planar diplexer that is integrated in a millimeter-wave transceiver front end operating in frequency division duplexing mode for point-to-point wireless backhaul applications. The proposed diplexer is composed by 5th-order SIW bandpass channel filters providing high channel-to-channel isolation. SIW-to-microstrip transitions provide diplexer integration with the transceiver front end. In [19], authors presented the design and modeling procedures of the 5th-order SIW bandpass filters with center frequencies at 59.8 GHz and 62.2 GHz, providing 1 GHz bandwidth. Electromagnetic simulation results reported very good performance in terms of passband insertion loss and return loss, as well as in terms of out-of-band rejection. Based on these results, authors in [20] provided an initial approach of a 60 GHz SIW planar diplexer providing preliminary designs and electromagnetic simulation results. Diplexer design was further optimized and fabricated, and in this paper measurement results are provided and compared with simulation ones.

2. The 60 GHz SIW General Structure

SIW structure is fabricated by using two periodic rows of metallic vias connecting the top and bottom ground planes of a dielectric substrate. The top side of a general SIW structure is depicted in Figure 1.

SIW width, α_{SIW}, is calculated based on the corresponding rectangular waveguide width, α, as follow:

$$\alpha_{\mathrm{SIW}} = \frac{\alpha}{\sqrt{\varepsilon_r}}, \tag{1}$$

where ε_r is the substrate dielectric constant. The replacement of conductive walls by metallic vias leads to the variation of SIW structure width. The equivalent width is called effective width and depends on design parameters. According to [7], the SIW effective width, α_{eff}, is given by

$$\alpha_{\mathrm{eff}} = \alpha_{\mathrm{SIW}} - 1.08 \cdot \frac{d_v^2}{p_v} + 0.1 \cdot \frac{d_v^2}{\alpha_{\mathrm{SIW}}}. \tag{2}$$

Via diameter d_v and pitch via p_v should be appropriately set in order to ensure that there is no radiation leakage between metallic vias due to diffraction. In [21], the following design rules are given in order to avoid such effects:

$$d_v = \frac{\lambda_g}{5}, \qquad p_v \leq 2 \cdot d_v. \tag{3}$$

In this paper, dielectric substrate Rogers RT/duroid 5880 (ε_r = 2.2; $\tan\delta$ = 0.0009; dielectric thickness h = 0.508 mm) is used. Taking into account that the 60 GHz frequency band rectangular waveguide (WR-15) width is α = 3.759 mm and applying (1)–(3), the SIW basic parameters for the 60 GHz band are calculated and summarized in Table 1.

3. The 60 GHz SIW Planar Diplexer

3.1. SIW Channel Filter Modeling. The diplexer consists of two bandpass channel filters with center frequencies at 59.8 GHz (receive chain) and 62.2 GHz (transmit chain), respectively. Channel filter bandwidth requirement is 1 GHz, and filter order is 5. Figure 2 depicts the 5th-order SIW bandpass filter model.

Filter modeling was presented by authors in [19], and it is based on the n-order IRIS waveguide bandpass filter analysis suggested in [22]. According to that, the equivalent circuit of an IRIS which is placed parallel to the electrical field is a shunt inductor. Waveguide cavity length l_i, ($i = 1, \ldots, n$) and IRIS aperture width d_i ($i = 1, \ldots, n + 1$) are calculated based upon filter specifications. The suggested analysis was suitably adjusted in [19], in order to calculate the corresponding l_i and d_i for the SIW bandpass channel filters. Given that the guided wavelength in the rectangular waveguide is

$$\lambda_{g\mathrm{WG}} = \frac{\lambda_0}{\sqrt{1 - (\lambda_0/2\alpha)^2}}, \tag{4}$$

where λ_0 is the free space wavelength, α is the rectangular waveguide width, and the guided wavelength in the SIW structure is given by

$$\lambda_{g\mathrm{SIW}} = \frac{\lambda_{\mathrm{diel}}}{\sqrt{1 - (\lambda_{\mathrm{diel}}/2\alpha_{\mathrm{eff}})^2}}, \tag{5}$$

where α_{eff} is the SIW effective width and λ_{diel} is given by

$$\lambda_{\mathrm{diel}} = \frac{\lambda_0}{\sqrt{\mu_0 \varepsilon_r}}. \tag{6}$$

Based on given filters' specifications and using (4)–(6), l_i and d_i were calculated. Design was performed using Ansoft HFSS v.12, while an optimization procedure was followed in order to meet the desired specifications. Simulation results reported that, for the transmit channel, filter center frequency was at 62.2 GHz providing 1 GHz bandwidth. Insertion loss was 1.5 dB, while return loss was varying below 20 dB in the passband. Filter rejection at transmit channel, filter center frequency (59.8 GHz) was 90 dB. Concerning the receive channel filter, center frequency was at 59.8 GHz with 1 GHz

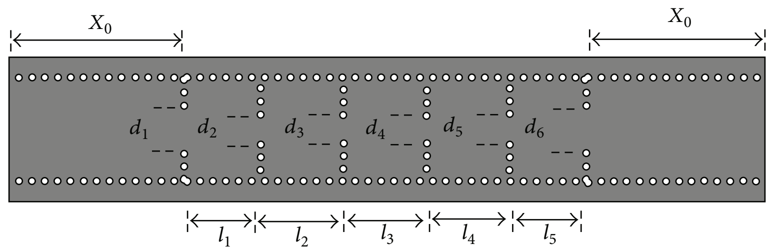

Figure 2: The 5th-order SIW bandpass channel filter model.

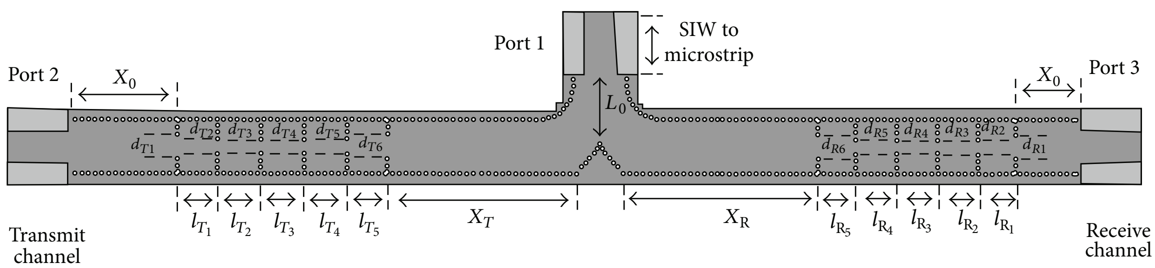

Figure 3: The SIW planar diplexer design model.

bandwidth. Insertion loss was about 2 dB, while return loss was varying below 20 dB in the passband. Filter rejection at receive channel filter center frequency (62.2 GHz) was 66 dB.

3.2. Diplexer Integration. In Figure 3, the SIW planar diplexer model is presented.

Design parameters for channel filters ($l_i, i = 1, \ldots, n$, and $d_i, i = 1, \ldots, n+1$) were calculated in [19]. Parameter X_0 represents the space length at the SIW channel filter ports before the edge cavities, and as it was observed during design procedure, it is a critical parameter for filter impendence matching. As it was shown in [20], authors initially set X_0 to be equal to $\lambda_{g\mathrm{SIW}}/2$. The optimization procedure proved that optimum performance in terms of input return loss was given when X_0 was precisely equal to $\lambda_{g\mathrm{SIW}}$.

A SIW T-junction was designed in order to integrate the channel filters within diplexer and to ensure the minimum coupling between them. As it was presented in [20], the key for the T-junction design is to ensure TE10 mode propagation as well as incident electromagnetic waves at channel filters to be equal amplitude and in phase. Figure 4 shows the SIW T-junction as well as the HFSS simulation electric field distribution within the structure.

The transition from common port towards filter chains is based on mitering technique in order to reduce the reflections from transmit and receive ports. The first center via is placed at a distance L_0 from the diplexer common port. According to [20], distance L_0 is critical for common port performance in terms of input return loss. L_0 was initially set equal to SIW wavelength $\lambda_{g\mathrm{SIW}}$, and based on tuning, the optimum value for L_0 was found. Parameters X_T and X_R represent the distance between the T-junction and the first cavity of the transmit and receive channel filters, respectively, and they were initially set equal to $2\lambda_{g\mathrm{SIW}}$. Optimization procedure provided values that corresponded to lower reflections in diplexer ports.

50 Ohm SIW-to-microstrip transitions were predicted for diplexer ports in order for the diplexer to be connected with test equipment during performance verification. As it can be seen in Figure 5, SIW-to-microstrip transition consists of one transmission line with dimensions a_1 and w_1 and one tapered line with dimensions a_2 and w_2.

The suitable SIW-to-microstrip transition design enables TE10 mode to be propagated into the SIW structure. The microstrip width, w_i ($i = 1, 2$), is calculated based upon the following equation:

$$w_i = \frac{Z_k \cdot h}{\sqrt{e_{\mathrm{ff}}} Z_0}, \quad (7)$$

where Z_k is the free space impedance ($Z_k = 376.8$ Ohm), h is dielectric substrate thickness provided in Table 1, and e_{ff} that is effective permittivity of the dielectric substrate for $w > h$ is given by

$$e_{\mathrm{ff}} = \varepsilon_r. \quad (8)$$

A diplexer model without transitions was designed and simulated using HFSS in order to calculate SIW structure input impedance Z_0. Simulation gave $Z_0 = 48$ Ohm for all diplexer ports, and using (7), w_2 was computed. $Z_0 = 50$ Ohm was considered for the SMA connector, and using (7), w_1 was computed.

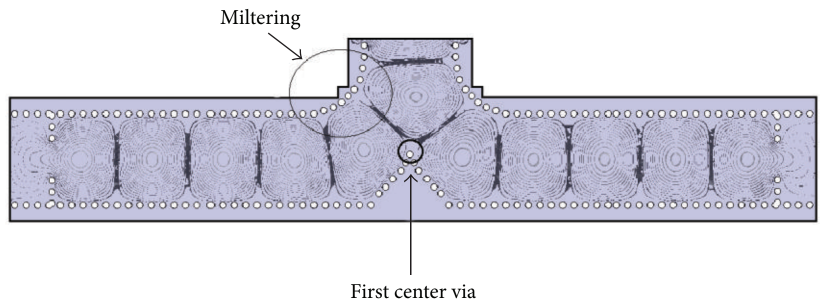

Figure 4: The electric field distribution within SIW T-junction.

Table 1: Summary of SIW design parameters at 60 GHz frequency band.

Parameter	Symbol	Value	Unit
Dielectric substrate		RT/duroid 5880 (ε_r = 2.2; tan δ = 0.0009; h = 0.508)	
Pitch via	p_v	0.35	mm
Via diameter	d_v	0.2	mm
SIW width	α_{SIW}	2.8	mm
SIW effective width	α_{eff}	2.678	mm

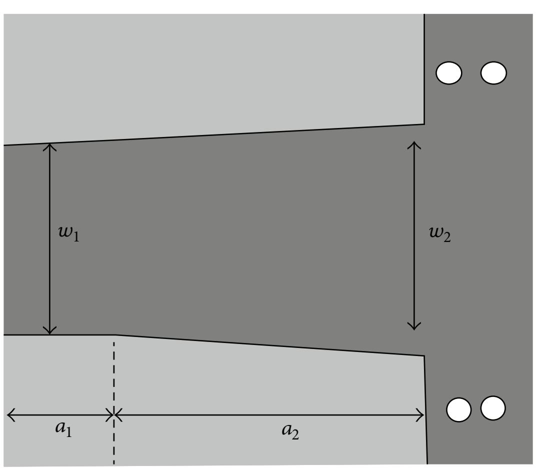

Figure 5: The SIW-to-microstrip transition model.

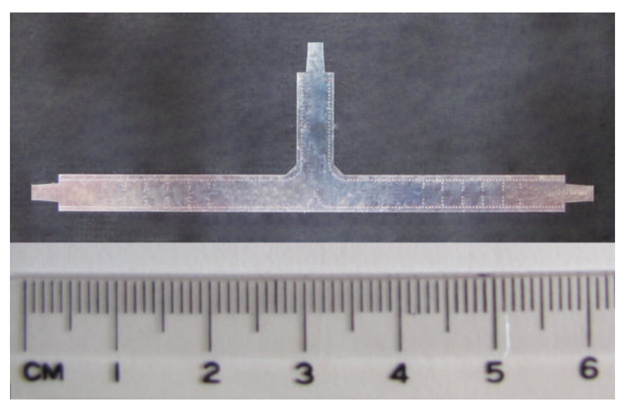

Figure 6: The 60 GHz SIW planar diplexer.

The total microstrip transition length ($a_1 + a_2$) is equal to one microstrip wavelength λ_g, where

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}}. \tag{9}$$

Optimization given for a_1 and a_2 is as follows:

$$\alpha_1 = \frac{\lambda_g}{4}, \qquad \alpha_2 = 3 \cdot \frac{\lambda_g}{4}. \tag{10}$$

In Table 2, all design parameters for SIW diplexer are summarized.

4. Results

The 60 GHz SIW planar diplexer is depicted in Figure 6.

Figure 7 shows diplexer performance in terms of common port return loss (S_{11}) as well as in terms of channel-to-channel isolation (S_{23}). Both measurement and simulation results are provided, and as it can be seen, they are in good agreement. Common port return loss varies below 10 dB in the passbands, while channel-to-channel isolation varies below 60 dB in the whole frequency range.

Figure 8 shows transmit and receive ports' insertion loss (S_{12} and S_{13}, resp.). As it can be seen, there is a shift in the predefined center frequencies of the passbands, while the achieved relative bandwidths are 1.67% and 1.6%, respectively. The observed frequency down shift, which is approximately 300 MHz, is caused by fabrication accuracy and tolerances of manufacture, parameters that introduce such effects especially in the millimeter-wave frequency band. Insertion loss is about 4 dB for both transmit and receive passbands. The transmit channel out-of-band rejection is 55 dB at 62.2 GHz,

Table 2: Summary of the 60 GHz SIW planar diplexer design parameters.

		X_0 (mm)	l_1 (mm)	l_2 (mm)	l_3 (mm)	l_4 (mm)	l_5 (mm)	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_5 (mm)	d_6 (mm)
Channel filters	Receiver filter (62.2 GHz)	4.70	2.07	2.24	2.26	2.24	2.07	1.09	0.61	0.54	0.54	0.61	1.09
	Transmitter filter (59.8 GHz)	4.70	2.07	2.24	2.26	2.11	2.07	1.06	0.59	0.52	0.52	0.59	1.06
			w_1 (mm)			w_2 (mm)			a_1 (mm)			a_2 (mm)	
SIW-to-microstrip transitions	Receive port		1.57			1.92			0.8			2.4	
	Transmit port		1.57			1.92			0.8			2.4	
	Common port		1.57			1.92			0.8			2.4	
				L_0 (mm)			X_T (mm)				X_R (mm)		
T-junction				3.55			9.8				10.07		

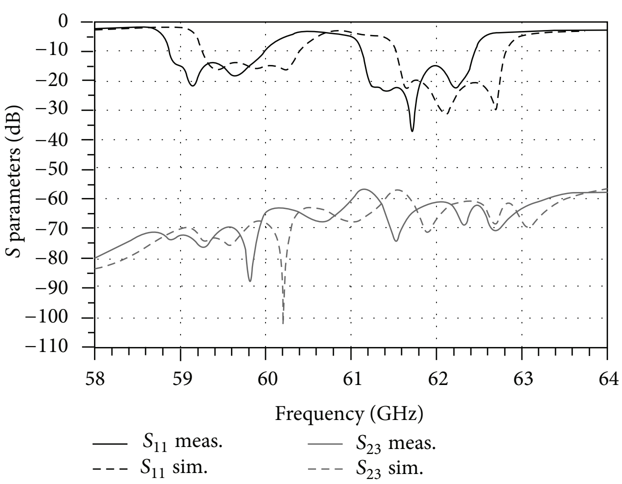

Figure 7: Diplexer performance in terms of common port return loss and channel-to-channel isolation.

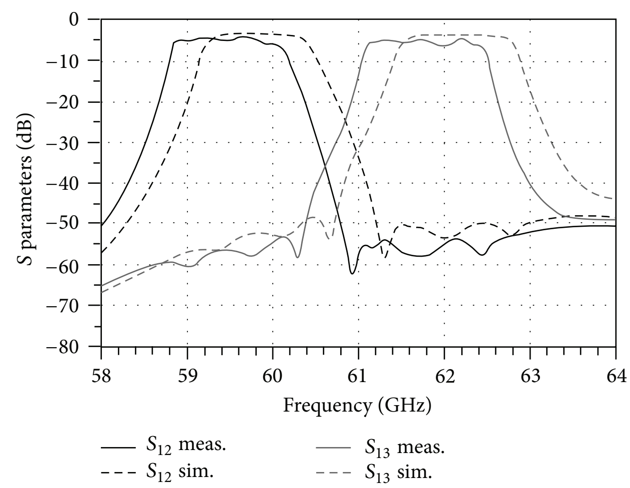

Figure 8: Diplexer performance in terms of receive and transmit ports' insertion loss.

while the receive channel out-of-band rejection is 58 dB at 59.8 GHz.

Finally, Figure 9 shows diplexer performance in terms of transmit and receive ports' return loss (S_{22} and S_{33}, resp.). As it can be seen, S_{22} and S_{33} vary below 10 dB in transmit and receive passbands, respectively.

5. Conclusion

The design, development, and fabrication of a 60 GHz, millimeter-wave planar diplexer based on the substrate integrated waveguide technology are presented in this paper. Measurement results report very good performance in terms of insertion loss in the channel filters passbands and return loss in all diplexer ports' bands. The high channel filter bandwidth in combination with the achieved high out-of-band rejection and high channel-to-channel isolation enables the usage of the proposed diplexer as channel separator in high bandwidth millimeter wave transceiver front ends.

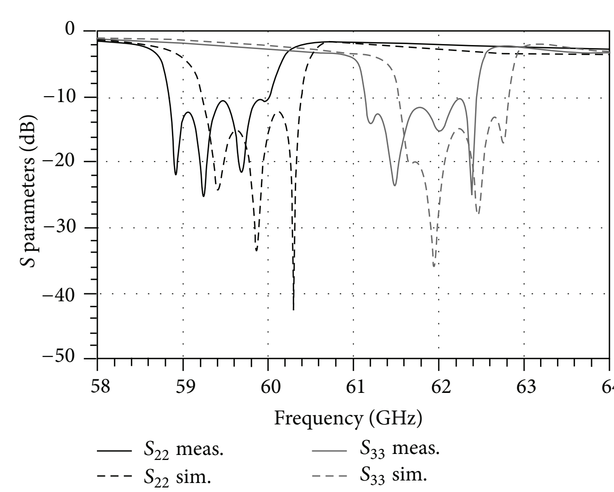

Figure 9: Diplexer performance in terms of receive and transmit ports' return loss.

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