Reflection attenuator based on substrate integrated waveguide applied in Ku band

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Based on substrate integrated waveguide (SIW) technology, a reflection attenuator applied in Ku band is proposed here. The attenuator is composed of three SIWs and two SIW micro-strip converters using the FR4 substrate. The whole size of the attenuator is 31×8.0×1.6 mm, which is compact and easy to be integrated, meeting the requirements for miniaturizing the high-power microwave test instrument. The attenuation value of the attenuator was calculated using the transmission matrix and the equivalence relation between SIW and rectangle waveguide. Also the attenuator was simulated by high frequency structure simulator (HFSS) software and fabricated. The measurement results are fit well with the ones by calculation and simulation.

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1. Introduction

The attenuator based on rectangle waveguide is very typical and widely applied in the signal receiving system and microwave test field [1], however the process and fabrication of the attenuator is strictly precise that lead to high cost, not convenient for system integration, incongruity for mass production [2]. Substrate integrated waveguide is composed of a low loss dielectric substrate, two parallel metal plates which are covered on top and bottom of the substrate and two rows of conducting cylinder or slots which are embedded in the two sides of the substrate. The propagation characteristics of SIW are similar to the rectangular waveguide. SIW is maintaining the advantageous characteristics of rectangular waveguide such as low loss, high Q and high power capacity, while the SIW also present additional advantages of micro-strip line such as low profile, compact and high power capacity [3]. Recently SIW has been the hot research topic in the microwave field and extensive research have been made, such as: filter [4], oscillator [5], power divider [6], oscillator [7], circulator [8], mixer [9], amplifier [10], antenna [11] and so on, inject new vitality into the design of millimeter-wave circuits and system [12].

Based on the SIW technology, an attenuator which applied in broadcasting satellite service (11.7 to 12.2GHz) is proposed, designed and fabricated. The proposed attenuatoris on a FR-4 substrate, which is composed of three SIWs and two SIW-microstrip converters. The attenuator is easily integrated with the planar devices and compact with the size 31×8.0×1.6 mm.The theoretical attenuation value of theproposed attenuator is -14.6dB at 12GHz. The simulated attenuation value of theproposed attenuator is -15.2dB at 12GHz.The measured attenuation value of thefabricated attenuator is -16.7dB at 12GHz.

2. Theoretical design

The geometry of a conventional rectangular waveguide attenuator is depicted in Fig. 1, which is composed of input/output waveguides and an attenuated waveguide. The cutoff frequency of the attenuated waveguide is higher than the propagating signal. The attenuation value A can be calculated as follows [13]:

$$\begin{aligned} A &= -20\log e^{-\alpha l} \\ k &= \frac{2\pi f}{c}\sqrt{\varepsilon_r} \\ \alpha &= \sqrt{\left(\frac{\pi}{d}\right)^2 - k^2} \end{aligned} \tag{1}$$

k is the wave number, α is the attenuation constant, c is the velocity of light, f is the operating frequency, ε_r is the medium conductivity, d is the width of attenuated waveguide, l is attenuated waveguide length.

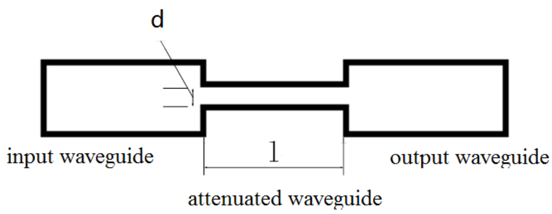

Fig. 1. Geometry of rectangular waveguide attenuator

The geometry of SIW is depicted in Fig. 2.

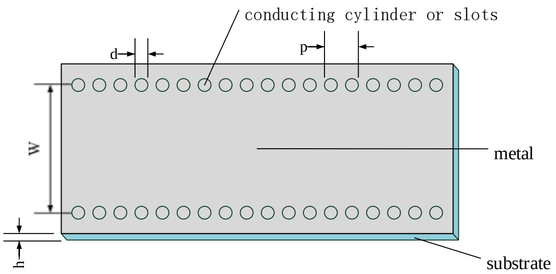

Fig. 2. Geometry of SIW

The equivalence relationship between SIW and rectangular waveguide is [3]:

$$w_{eff} = w - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{w} \qquad (2)$$

Where, w_{eff} is the width of rectangular waveguide, w is the width of SIW, d is the diameter of the cylinder or slots and the p is the separation distance of the cylinder or slot.

By using the equivalence relationship between SIW and rectangular waveguide, the novel attenuator based on SIW is designed as shown in Fig. 3. In order to make the attenuator connecting well with other circuits, two SIW micro-strip converters are used here. Therefore, the attenuator is composed of three SIWs and two SIW micro-strip converters using the FR4 substrate. The whole size of the attenuator is 31×8.0×1.6 mm. The detailed dimensionsare decided as: w=6.5 mm; w_1=3.23 mm; w_2=2.7 mm; w_3=3 mm; l=1.875 mm; l_1=1.9 mm; d=0.2 mm; p=0.4 mm.

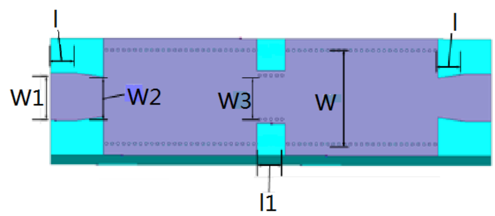

Fig. 3. Geometry of Reflection attenuator based on SIW

3. Theoretical analysis

To calculate the attenuation value of the proposed attenuator, Mehdi Salehi's method was used here [14]. Mehdi Salehi had simplified the modeling of the unit cell of the SIW. The open area out of adjacent via holes is treated as a rectangular unit, as well as the another part of the unit cell, as shown in Fig. 4.

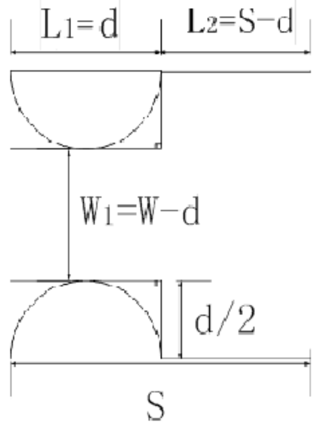

Fig. 4. Simplified model of SIW

The width of the two rectangular waveguide units is W_1 and W_2 respectively, where w_1=w-d, w_2=w. The length and the thickness of the unit which contain via hole is L_1=d and H respectively, the length and the thickness of the unit which not contain via hole is L_2=S-d and H respectively, by ignoring the high-order mode, the ABCD matrix of the unit can be given [14]:

$$E_m = \begin{bmatrix} A_m & B_m \\ C_m & D_m \end{bmatrix} = \begin{bmatrix} \cos(\beta_m L_m) & \frac{j\omega\mu}{\beta_m}\sin(\beta_m L_m) \\ \frac{j\beta_m}{\omega\mu}\sin(\beta_m L_m) & \cos(\beta_m L_m) \end{bmatrix} \qquad (3)$$

where:

$$W_m = \begin{cases} W - d & m = 1 \\ W & m = 2 \end{cases}$$

$$L_m = \begin{cases} d & m = 1 \\ p - d & m = 2 \end{cases}$$

$$\beta_m = \sqrt{\left(\omega^2\mu\varepsilon - \left(\frac{\pi}{W_m}\right)^2\right)}, \qquad m = 1, 2$$

Then the ABCD matrix of SIW could be given by the ABCD matrix cascading of SIW units:

$$F = \begin{bmatrix} A_F & B_F \\ C_F & D_F \end{bmatrix} = \left[E_1 \cdot E_2\right]^n \qquad (4)$$

So the S matrix can be derived by the ABCD matrix [13]:

$$S_F = \begin{bmatrix} S_{11}^F & S_{12}^F \\ S_{21}^F & S_{22}^F \end{bmatrix} = \frac{1}{A_F + B_F + C_F + D_F}\begin{bmatrix} A_F + B_F - C_F - D_F & 2\det F \\ 2 & D_F + B_F - C_F - A_F \end{bmatrix} \qquad (5)$$

For SIW attenuator shown in Fig. 4, sign the three parts of the SIW as A, B and A, for the SIW united by the three parts of SIW in sequence of A, B, A, its S_{21} parameter can be given:

$$S_{21} = \frac{\left(S_{21}^{A}\right)^{2} \cdot S_{21}^{B}}{\left(S_{11}^{B} \cdot S_{22}^{A} - 1\right)\left(S_{11}^{A} \cdot \left(S_{22}^{B} - \left(S_{12}^{B} \cdot S_{21}^{B} \cdot S_{22}^{A}\right) / \left(S_{11}^{B} \cdot S_{22}^{A} - 1\right)\right) - 1\right)} \quad (6)$$

4. Results

The designed performance of the proposed SIW attenuator is attenuating -15dB at 12GHz and attenuating lower than -14.5dB infrequency coverage from 11.7 to 12.2GHz (broadcasting satellite service). The attenuator was fabricated on a FR-4 substrate with 4.4 dielectric constant, 0.01 dielectric loss tangent and 1.6 mm thickness.

The theoretical attenuation value of the proposed attenuatoras well as thesimulation results which issimulated by HFSS is depicted in Fig. 5. It can be seen from Fig. 5 that the theoretical and simulated attenuation value at 12 GHz are -14.62dB and -15.2dB respectively. In the operating frequency range, both of the theoretical and simulated attenuation value are lower than -14.5dB.

Aprototype of the proposed attenuator was fabricated by PCB engraving machine and via hole metallization. Here the whole size of the attenuator is 31×8.0×1.6 mm as shown in the Fig. 6. The fabricated attenuator was measured by Agilent® vector network analyzer E5071C, and the measurement results are shown in the Fig. 5. The measured attenuation value of the fabricated attenuator is -16.7dB at 12GHz. In operating frequency range, the measurement attenuation value is lower than -16dB. Due to the loss of craft and weld of SMA adaptor, the measurement attentuation value is slightly lower than the theoretical and simulated results, but it was also very close to the expection.

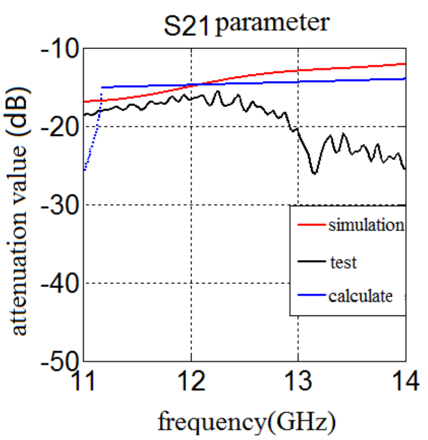

Fig. 5. Simulation result of attenuator (red line is the result of simulation, black line is the result of measurement, blue line is the result of theoretical arithmetic)

Fig. 6. Geometry of attenuator

5. Conclusion

Based on SIW technology, a attenuator used in Ku band was proposed, designed and fabricated. The proposed attenuator was composed of three SIWs and two SIW micro-strip converters. The performance of the proposed attenuator has been verified by theoretical calculation, simulation and measurement. Compared with the conventional attenuators based on rectangular waveguide, the SIW attenuator here exhibits many advantages such as compact size, cheap fabricating and easily integrated with the planar devices.

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