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Low-Cost Substrate Integrated Waveguide Equalizer Based on the Indium Tin Oxides Conductive Film

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Abstract—A low-cost and mechanical reconfigurable substrate integrated waveguide (SIW) equalizer is presented and studied in this work. Different from the previous SIW equalizers using Tantalum Nitride (TaN) or absorbing material as the resistive element, indium tin oxides (ITO) are introduced into SIW equalizer. The absorbing material will deform under uneven pressure due to the structural softness of material, resulting in instable equalizing values. Compared with the absorbing material, ITO provides more structural stability, excellent high frequency characteristic, and can be easily integrated with traditional printed circuit board (PCB). Furthermore, an equalizer with reconfigurable equalizing values can be realized by adjusting ITO materials with different impedances. A SIW equalizer based on ITO Conductive Film, operating from 26 to 40 GHz, has been designed, fabricated, and experimentally verified. For measurement results, the return losses are better than −17.4 dB with 3, 6, and 10 dB equalizing values respectively over the entire Ka-band, and the insertion losses at the frequency point of 40 GHz are −2.89 dB, −4.80 dB, and −7.37 dB, respectively. The proposed equalizer presents the advantages of mechanical reconfigurable, low cost, and high stability. In addition, ITO Conductive Film is a good candidate for the design of high millimeter-wave band equalizer.

1. INTRODUCTION

With an increase of the frequency, the gain of the RF/millimeter-wave transmitter often decreases. In this case, the equalizer with positive transmission loss slopes is usually required to develop an RF-end circuit system [1]. It can be used to compensate the amplitude inconsistency of components and circuits, which make the output power fluctuate a little in the working frequency band [2]. In previous reports [1–5], several equalizers based on microstrip have been reported. In [1], an amplitude tilt active equalizer based on p-i-n diode was proposed, which can realize the equalizing value of 8 dB over 3–5 GHz. To increase the bandwidth, stepped impedance resonator (SIR) lines are introduced to equalizer in [2, 3]. In [4], a compact equalizer was fabricated using complex low-temperature cofired ceramic (LTCC) technology and composite right-left handed transmission line. It can provide the equalization of 12 dB and a minimum loss of 1.25 dB over 2–6 GHz. In order to reduce costs, an equalizer of terminal open line resonators based on Rogers RT/duriod 5880 was proposed in [5]. The return loss and equalization were 15.5 and 2.5 dB over the frequency range from 6 to 18 GHz. However, the performance of the above equalizer using diodes [1] and thin film resistors [2–5] would deteriorate at high frequency due to the parasitic effect.

In recent years, some papers about SIW equalizer have been reported [6–9]. SIW is an emerging type of rectangular dielectric-filled waveguide. It is synthesized in a planar substrate with arrays of metallic vias to realize bilateral edge or side walls. SIW-based designs have many advantages, such as small size, high Q-factor, and low insertion loss [10]. Therefore, it is a significant research direction

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to apply SIW in more fields including equalizer. In [7], a compact equalizer based on half mode substrate integrated waveguide (HMSIW) was designed, and the insertion loss is high (the maximum insertion loss was 12.5 dB) because of the energy leakage of the opening structure of HMSIW, and the operating frequency band is narrow (12.5–14.5 GHz). By introducing surface resistance instead of copper layer, a broadband SIW equalizer fabricated on a ceramic substrate was designed at 26–40 GHz in [8]. However, its cost was relatively high. In addition, the structure of equalizer based on ceramic substrate is unadjustable, so each size of equalizer can only correspond to a fixed equalizing value. In previous work [9], SIW equalizers used absorbing material as the resistive element, and the absorbing material was sandwiched with PCB and metal structure for the requirement of equalizer fabrication. As a consequence, the equalizing values fluctuated under uneven pressure due to the softness of absorbing material.

In this paper, ITO conductive film is adopted as the resistance material of equalizer. Being different from absorbing material, ITO conductive film, as a low-cost material, has the characteristics of broadband resistance tuning range and stability in high frequency band. ITO conductive film is an N-type semiconductor transparent film, which can be deposited on surfaces of devices by physical vapor deposition such as electron beam evaporation or sputter deposition [11]. By adjusting the thickness or the ratio of Ln_2O_3 and SnO_2 to get different values of resistance [12], the ITO film can be widely used in different applications, such as microwave absorber, antenna, and terahertz generation [13–16]. A microwave absorber was designed in [13], in which the peak absorption frequency can be tuned by changing the resistance of ITO films. Compared with absorbing materials and resistors, ITO has stable performance at high frequency band. Moreover, ITO film has been used in the design of terahertz (THz) devices [15, 16] because of its specific characteristics of large resistance tuning range at high frequency band. A hybrid metasurface incorporating an epsilon-near-zero (ENZ) indium tin oxide (ITO) is used to manipulate the THz waves [16]. Those works demonstrate the practicability of ITO in millimeter wave/THz band.

In this work, by introducing ITO conductive film as surface resistance in particular location of SIW, a low-cost SIW equalizer with high stability and reconfigurable equalizing value has been realized at the Ka-band. As we know, it is the first report about applying ITO conductive film to SIW equalizer. In the following sections, the design and simulation of a low-cost SIW equalizer based on ITO will be introduced in detail.

2. SIW EQUALIZER DESIGN AND SIMULATION

The design theory of SIW equalizer and ITO material to achieve an equalizer is analyzed below. Since the TE_{10} mode field distribution in rectangular waveguide (RW) is similar to SIW, the analysis attenuation characteristic of SIW can be obtained by analyzing the attenuation characteristics of RW. The surface impedance of RW is very low ($R_s \approx 0\,\Omega$), so the top of RW is loaded with resistive ITO material to increase the loss, as shown in Figure 1.

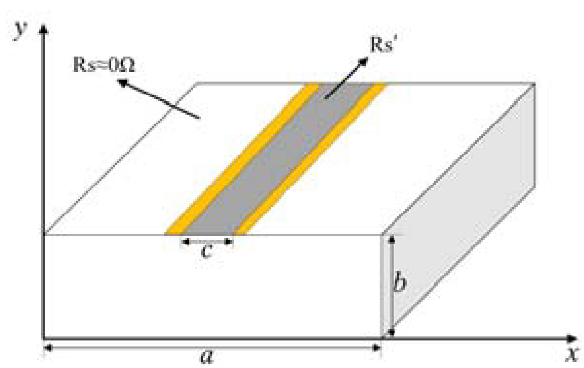


Figure 1. ITO material introduced on the surface of RW.

Let $c = k \cdot a\,(0 \leq k \leq 1)$, and the attenuation constant α can be given by:

$$\alpha = \frac{R'_S}{2b \cdot \eta} \cdot \frac{k + \frac{1}{\pi}\sin(\pi k) - \frac{2}{\pi}\left(\frac{f_c}{f}\right)^2 \sin(\pi k)}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \tag{1}$$

where R_s, R'_s, η, f_c represent the surface resistance of metal in RW, the surface resistance in ITO material, the intrinsic impedance of RW, and the cut-off frequency, respectively.

Let $F = f_c/f\,(0.5 < F < 0.85)$, and $A = \frac{R'_S}{2b \cdot \eta}$, the attenuation constant α from Equation (1) can be simplified as:

$$\alpha = A \cdot \frac{k + \frac{1}{\pi}\sin(\pi k) - \frac{2}{\pi}F^2 \sin(\pi k)}{\sqrt{1 - F^2}} \tag{2}$$

From the above formulas, by changing surface resistance values, the equalizer can obtain the desired attenuation value. Because of the wide impedance characteristics of ITO materials, it is suitable for designing different equalizers.

Seen from Figure 2, the ITO conductive film is fixed between PCB and rubber sheet. The top and bottom layers are both metal covers. The gap on PCB can be completely covered by 0.125-mm-thick ITO material. The SIW equalizer is achieved on a Rogers 5880 substrate with relative permittivity of 2.22, loss tangent of 0.009 and thickness of 0.254 mm.

Figure 2. Assembling method of SIW equalizer.

Figure 3(a) shows the top view of SIW equalizer. A matching metallized via is introduced on both sides of the connecting edge. The two matching metallized vias on the same side are axisymmetric with the center line of the SIW, and there are two matching metallized holes at one end, with a total of four at both ends. Energy propagation losses can be reduced when the electromagnetic wave propagates in TE_{10} mode in the SIW equalizer, because the electromagnetic wave is confined in a rectangular cavity formed by two rows of metal vias and the two metal layers. L_t is the length of transition line, and W_t is the length of the connecting edge between the transition line and the SIW. The SIW is connected with a $50\,\Omega$ microstrip line through the transition line to improve the return loss.

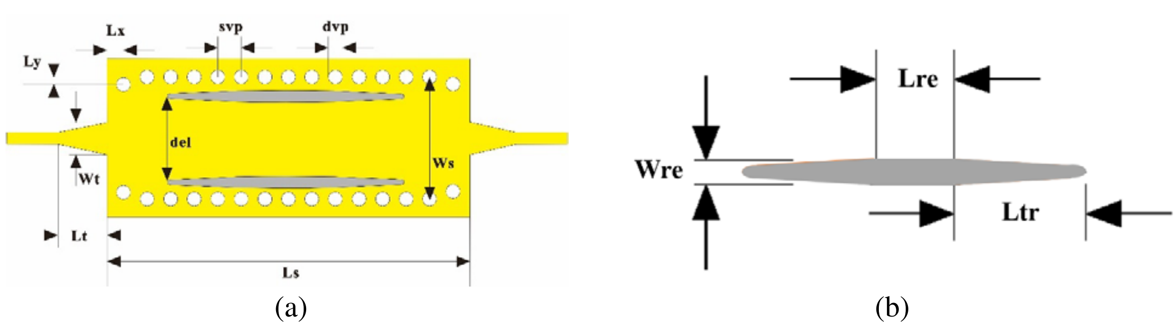


Figure 3. Top view of SIW equalizer. (a) Structure of SIW equalizer; (b) Air slot.

In order to increase the loss during propagating, an energy dissipation element ITO conductive film with $40\,\Omega/\mathrm{sq}$ is designed in this work. Figure 3(b) shows the shape of square resistance area, when the electromagnetic wave propagates in the SIW. The ITO film on the two grooves can attenuate the energy, and this attenuation is closely related to the working frequency. At the same time, the surface resistance introduced by the ITO film placed near the metal via can significantly relieve the insertion loss at high-frequency band.

As shown in Figure 3, two grooves have been designed on the top layer, which are symmetrical around the center line of the SIW equalizer. Compared with the shuttle shape in [9], the groove shape of the proposed work is composed of a rectangle in the middle and isosceles triangles at both ends, and the vertex of the isosceles triangle is an arc. L_{re} is the length of the long side of the rectangle (the side parallel to the electromagnetic wave propagation direction); W_{sr} is the length of the wide side of the rectangle ($W_{re} < W_s/2$); L_{srt} is the height of the two triangles ($L_{re} + 2 \times L_{tr} < L_s$); and del is the distance between the center lines of the vertices of the isosceles triangles in the two grooves ($del < W_s$). The closer the ITO film is to the via holes, the lower the insertion loss is in the high-frequency band. For ITO conductive film, the values of L_{re}, L_{tr}, W_{re}, and del are related to the performance of SIW equalizer. Those parameters are designed carefully to improve the return loss of SIW equalizer.

Table 1. Dimensional values of SIW equalizer.

Rogers5880 substrate, $\varepsilon_\gamma = 2.2$, Ka band, (in mm)			
W_s	5.15	h	0.254
W_t	1.4	L_t	1.6
L_x	0.42	L_y	0.25
svp	0.8	dvp	0.5
del	3.4		
Equalizing value of 3 dB			
L_s	18.5	W_{re}	0.3
L_{re}	1.7	L_{tr}	4.52
Equalizing value of 6 dB			
L_s	23.3	W_{re}	0.5
L_{re}	3.5	L_{tr}	5.41
Equalizing value of 10 dB			
L_s	29.7	W_{re}	0.5
L_{re}	10.5	L_{tr}	5.41

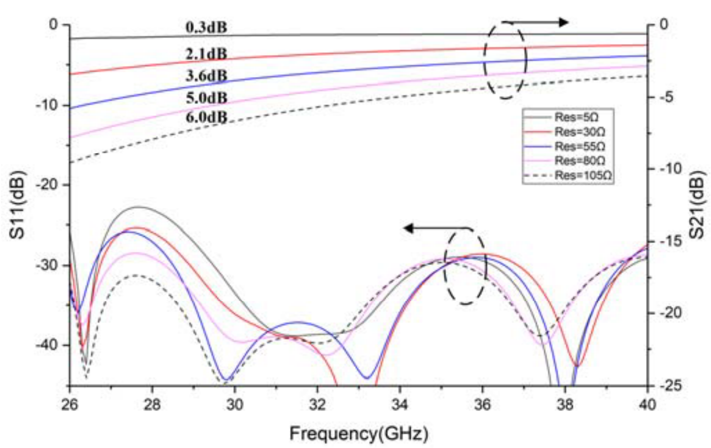


Figure 4. Effect of ITO impedance value on equalizing value.

According to simulation and optimization with the 3D electromagnetic simulation software, the optimal parameters are obtained, as given in Table 1. It shows the values of the dimension of SIW equalizer, square resistance area, and launch structure for the equalizing values of 3, 6, and 10 dB.

Figure 4 shows the S-parameters of the 3 dB equalizer with different resistance values of ITO film. In simulation, the model dimensions of 3 dB equalizer remain constant. It can be seen that a larger equalizing value can be achieved by adjusting the resistance value of ITO film, so the equalizing value of 6 dB can be implemented on the 3 dB equalizer by changing the ITO film with a resistance value of 105 Ω. It means that the mechanical reconfigurable SIW equalizer can be achieved by replacing the ITO film with different equalizing value.

3. MANUFACTURING AND MEASUREMENT

To experimentally test the performance of the proposed SIW equalizer, the prototypes are fabricated on a 0.254-mm-thick Rogers 5880 substrate. Figure 5 shows photographs of the fabricated SIW equalizers with different equalizing values. To obtain a higher equalizing value, the size of the equalizer will generally increase. However, this paper can achieve different equalizing values by changing the resistance

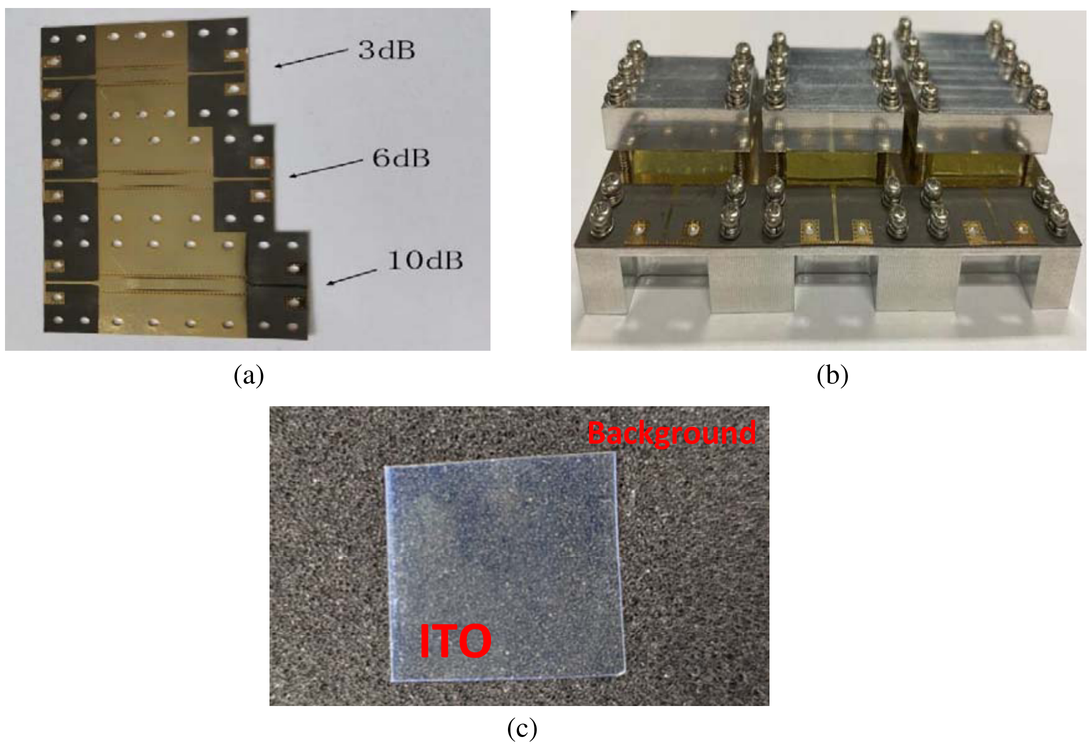
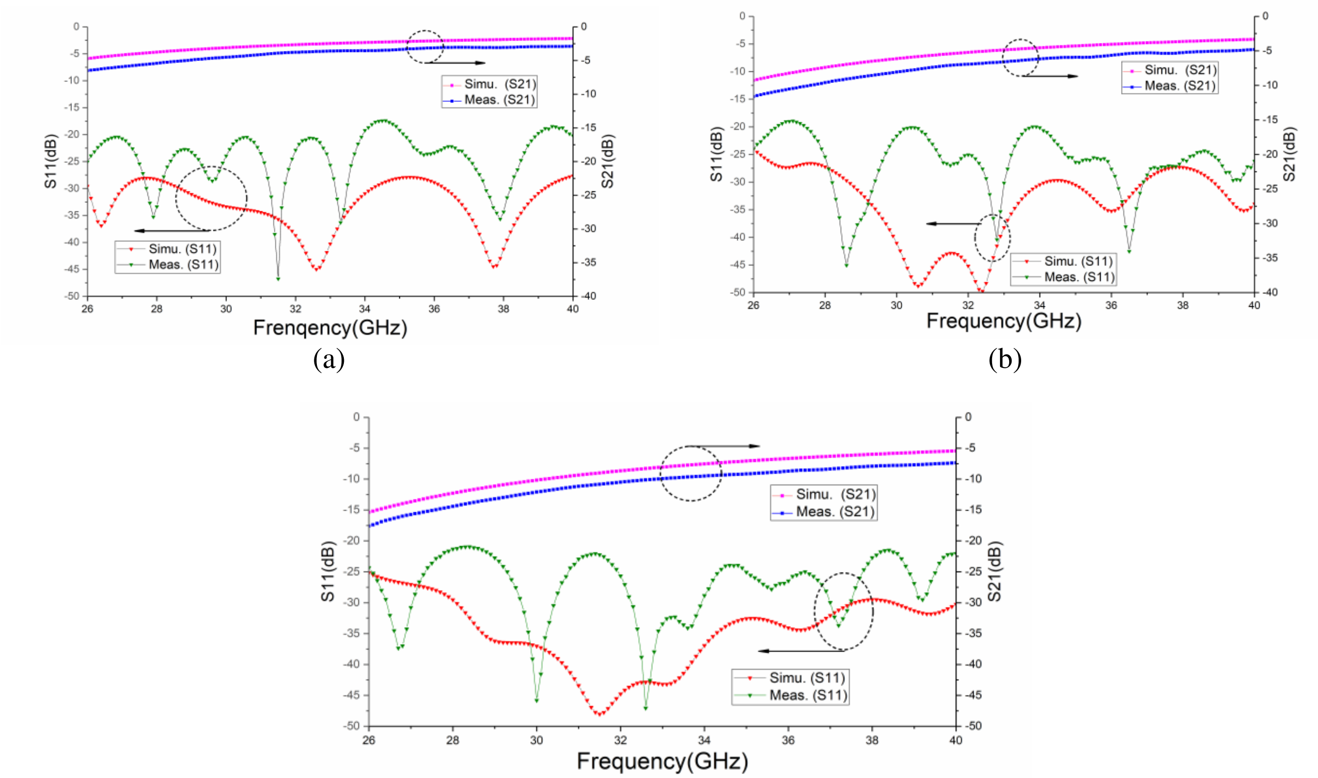


Figure 5. The image of SIW equalizer: (a) Photograph of the fabricated SIW equalizers; (b) Photograph of the fixed SIW equalizers; (c) Photograph of the ITO.

Table 2. The performance of SIW equalizer.

equalization value	S_{11} (simulated)	S_{11} (measured)	S_{21} (simulated)	S_{21} (measured)
3 dB	−27.66 dB	−17.40 dB	−2.99 dB	−3.61 dB
6 dB	−24.03 dB	−18.95 dB	−5.96 dB	−6.83 dB
10 dB	−25.17 dB	−20.95 dB	−9.92 dB	−10.25 dB



(c)

Figure 6. Simulation and measurement results: (a) The equalizing value is 3 dB; (b) The equalizing value is 6 dB; (c) The equalizing value is 10 dB.

Table 3. Comparison between other SIW equalizers.

Reference	Frequency band (GHz)	Equalizing values (Sim./Mea., dB)	S_{11} (Sim./Mea., dB)	Insertion losses at maximum freq. point (Sim./Mea., dB)	Test stability	Cost	Reconfigurability
5	6–18	2.5/non	$\leqslant -15.5$/non	4.5/non	Yes	Low	No
7	12.5–14.5	12.8/12.5	$\leqslant -14/-12.5$	non/non	Yes	Low	No
8	26–40	3/2.8	$\leqslant -25.5/-18.8$	1.73/1.67	Yes	High	No
		6/5.6	$\leqslant -22.2/-20.1$	3.33/3.15			
		10/9	$\leqslant -26.3/25.4$	5.22/5.02			
9	26–40	3/2.94	$\leqslant -16.5/-14.6$	1.2/2.32	No	Low	No
		6/6.55	$\leqslant -17.1/-16.0$	1.6/2.30			
		10/9.74	$\leqslant -18.9/-14.8$	2.03/2.77			
This work	26–40	3/3.61	$\leqslant -27.7/-17.4$	1.75/2.89	Yes	Low	Yes
		6/6.83	$\leqslant -24/-19$	3.34/4.80			
		10/10.25	$\leqslant -25.2/-21$	5.45/7.37			

value of ITO film without increasing the size. The simulated and measured S-parameters of SIW equalizers with 3 dB, 6 dB, and 10 dB are plotted in Figure 6. In the 26–40 GHz band, the measured S_{11} parameter is better than -17.4 dB. Compared with the simulated results of 3, 6, and 10 dB, the equalizing values of SIW equalizers, which are defined as the difference of transmission loss $|S_{21}|$ at the frequency points of 26 and 40 GHz, are 3.61, 6.83, and 10.25 dB, respectively. The equalizing errors are 0.61, 0.83, and 0.25 dB for equalizing values with 3, 6, and 10 dB over the whole Ka-band. The deviation between measurement and simulation can be attributed to the matching error of PCB, the change of surface resistance, and the impedance boundary of ideal resistance which is used to simplify the surface resistance model.

Table 2 shows the performance of SIW equalizers with different equalizing values at the frequency of 26–40 GHz, and the comparison results of several equalizers can be seen from Table 3. The equalizers shown in [5, 7] are all lower than millimeter-wave band. The SIW equalizers in [8, 9] have low insertion loss over the Ka-band. However, the cost of equalizer in [8] is relatively higher, and the performance of equalizer in [9] is unstable due to the softness of absorbing materials. Compared with other equalizers, the SIW equalizer in this paper has the advantages of being reconfigurable, easy to adjust, and low cost. In addition, ITO material can be applied at higher frequency band [15, 16], which makes it a good candidate for the design of a high millimeter-wave/THz band equalizer.

4. CONCLUSION

This paper proposes a low-cost SIW equalizer based on the ITO conductive film. The equalizer has good performances of lower cost, structural stability, mechanically reconfigurable equalizing value. As we know, this is the first report about applying ITO material to equalizer design. For the measurement results, the return loss of SIW equalizer in the whole Ka-band is better than −17.4 dB, while the transmission loss is better than −10.25 dB. This SIW equalizer can be used in millimeter-wave circuits and systems. It is a good way to apply ITO film for developing millimeter-wave SIW equalizer.

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