Kent Academic Repository

Full text document (pdf)

Link to record in KAR

http://kar.kent.ac.uk/38128/

Document Version

Author's Accepted Manuscript

Analysis of Loaded Substrate Integrated Waveguides and Attenuators

Ruo Feng Xu, A.J. Farrall and P. R. Young, Senior Member, IEEE

Abstract—This letter provides an approximate analysis of a slotted substrate integrated waveguide with periodic loading elements using the transverse resonance technique. The technique is used to design a travelling wave attenuator whereby pin diodes are capacitively coupled to the waveguide slot. By changing the bias, and therefore loading resistance, a very constant, variable attenuation is produced over the waveguide band.

Index Terms—Attenuator, Substrate Integrated Waveguide.

I. INTRODUCTION

SUBSTRATE integrated waveguides (SIW) have become an important host transmission line for microwave and millimeter-wave circuits and systems, allowing hybrid waveguide and planar structures to be formed on a single laminate [1] or thick film substrate [2]. Many variations on the simple SIW have been proposed, with the purpose of increasing the operational bandwidth or decreasing the cross-sectional size of the waveguide, these include folded SIW [3] and half mode SIW [4]. Active and discrete devices can be integrated with SIW but usually require transitions to planar transmission lines such as microstrip or coplanar waveguide. These transitions can be relatively large and can suffer from radiation and mismatch losses. To overcome this problem, and integrate discrete components directly with SIW, the authors recently proposed the slotted SIW which has propagation characteristic similar to half mode SIW [5] but with the advantage of easy integration of lumped element devices across the slot.

This letter provides an approximate analysis of periodically loaded SSIW by means of the transverse resonance technique. The technique can be used for reactive, resistive or complex valued loading elements. To illustrate the usefulness of the method the technique is used to design a travelling wave attenuator in SSIW. The attenuator is shown to give a good constant, variable, attenuation across the 3-5 GHz range with return loss better than 15 dB.

Ruo Feng Xu is with the School of Information and Electrical Engineering, China University of Mining and Technology, 221116, China.

A.J. Farrall and P. R. Young are with the Broadband and Wireless Communications group, University of Kent, CT2 7LU, UK. (phone: +44 (0)1227-823290; fax: +44 (0)1227-456084; e-mail: p.r.young@kent.ac.uk).

II. THEORETICAL ANALYSIS

A. Transverse Resonance Analysis

We consider a slotted SIW where the slot is loaded with an impedance Z, see Fig. 1. The impedance Z could either be formed by a distributed structure, such as a resistive layer across the slot, or by periodically loaded discrete components, with period much less than a wavelength.
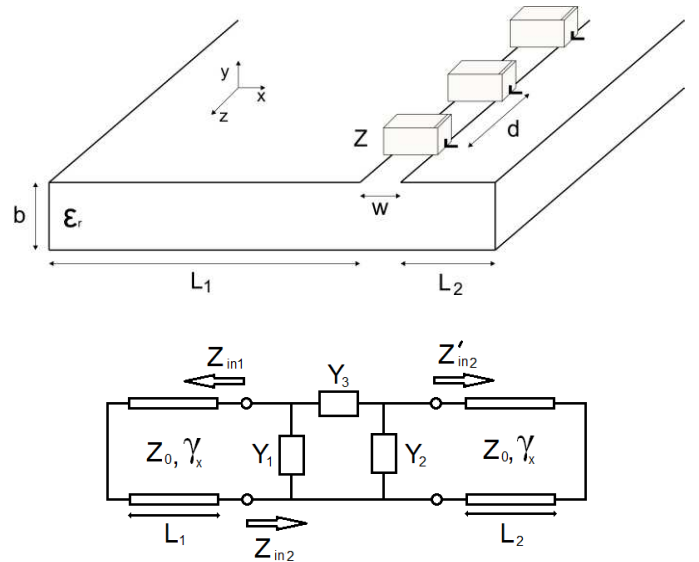

Fig. 1. Structure of periodically loaded slotted SIW and transverse resonance equivalent circuit.

Figure 1 also shows the equivalent circuit, in the transverse direction, of one unit cell of the periodically loaded slotted waveguide. We model the loaded slot by a pi-network where Y_1 and Y_2 take account of the effective shunt capacitances C_f of the fringing fields at the slot and Y_3 is the parallel combination of the loading element Z and slot capacitance C_s. It is well known that at resonance the condition $Z_{in1} = -Z_{in2}$ must be met, where Z_{in1} is the impedance seen looking towards the left from the left hand side of the slot and Z_{in2} is the impedance at the same point looking towards the right. By expressing the pi-network in terms of its ABCD parameters, the transverse resonance condition yields

$$\frac{AZ'_{in2} + B}{CZ'_{in2} + D} = -Z_0 \tanh \gamma_x L_1 \qquad (1)$$

where the impedance seen looking to the right, from the right hand side of the slot, is $Z'_{in2} = Z_0 \tanh \gamma_x L_2$. The unknown transverse propagation constant is $\gamma_x = \alpha_x + jk_x$ where α_x and β_x are the transverse attenuation and phase constants, respectively. A, B, C and D are the ABCD parameters of the pi-network and are related to Y_1, Y_2 and Y_3, see [6] for example.

Equation (1) is transcendental but can be solved for γ_x using the common root solving algorithms such as Gauss-Newton or Levenberg-Marquardt. Once γ_x is determined the longitudinal propagation constant can be calculated from $\gamma = \alpha + j\beta = (\gamma_0^2 - \gamma_x^2)^{1/2}$, where α is the longitudinal attenuation constant, β is the phase constant and γ_0 is the propagation constant of the substrate material, $\gamma_0 = j\omega\sqrt{\mu\varepsilon}$. If the loading element has a resistive element then γ_x is complex and equation (1) becomes a coupled non-linear equation in α_x and β_x. This can be difficult to solve without a guess value for the root solving algorithm. In order to do this, it is useful to first solve a reduced form of equation (1) by assuming that the shunt capacitances can be neglected, such that $A = D = 1$, $C = 0$ and $B = Y_3^{-1}$. Equation (1) then reduces to

$$Z_0 \tanh \gamma_x L_1 + Z_0 \tanh \gamma_x L_2 + Z_3 = 0 \qquad (2)$$

where $Z_3 = Y_3^{-1}$. This equation is more straightforward to solve than equation (1) since the poles of the tanh functions are known, allowing the range of values between which the solution γ_x lies to be easily determined. It is usual, that either the real or imaginary part of Z is more significant and consequently γ_x will be approximately real or imaginary. In this case a simple bisection technique can be used to calculate the roots of (2). This value can then be used as a starting guess for equation (1).

The stubs in the equivalent transverse circuit are effectively parallel plate waveguides of height b and cell width, d. The characteristic impedance is therefore $Z_0 = (b/d)(\mu/\varepsilon)^{1/2}$.

B. Results

Figure 2 shows comparisons between the transverse resonance technique and full wave solutions using CST. Both the effective permittivity, $\varepsilon_{eff} = (\beta/k_0)^2$, and attenuation constant, in dB cm^{-1}, of the fundamental mode are compared for a resistively loaded SSIW, where $k_0 = \mathrm{Re}\{\gamma_0\}$. The structure has height b = 1.575 mm, $L_1 = 15$ mm, $L_2 = 5$ mm, slot width w = 0.5 mm and relative permittivity $\varepsilon_r = 2.2$. Solutions are shown for resistive loading elements of 1000 Ω and 15 Ω separated by 5 mm. For accuracy, the values of C_f and C_s are obtained from full-wave simulation; however, they could be calculated easily using electrostatic approximations, see [7] for example. As can be seen there is good agreement between the full-wave solutions and values computed from equation 1.
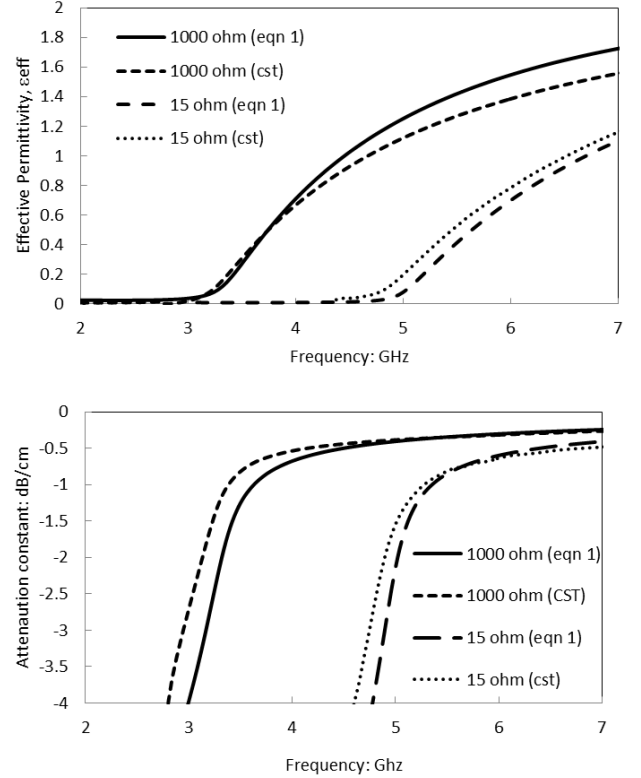

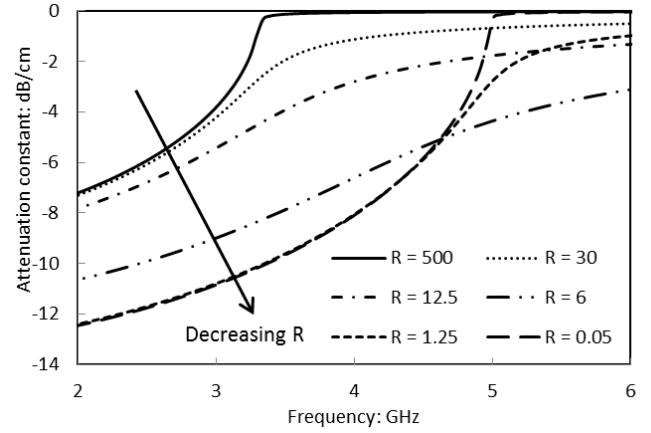Fig. 2. Comparison between full-wave and transverse resonansce values.

Fig. 3. The fundamental mode of a slotted waveguide loaded with a resistance of varying values using the transverse resonance technqiue.

Figure 3 shows the attenuation constant, in dB cm^{-1}, for varying values of loading resistance using the transverse resonance technique. The loading resistance is set to 500, 30, 12.5, 6, 1.25 and 0.05 Ωm. This is equivalent to loading the waveguide with resistors of value 10 000, 600, 250, 120, 25, and 1 Ω, respectively, for d = 5 mm. All the other parameters the same as above. When the resistance is large, the waveguide operates as a $TE_{1/2,0}$ type mode of a half mode waveguide of width L_1, with a small loss due to the resistance. As the resistance decreases, the loss increases until eventually the mode changes nature as the loading element becomes more like a short circuit. When this happens, the mode changes to a TE_{10} type mode of a $(L_1 + L_2)$ wide un-slotted waveguide. If

the resistance is varied over the 500-20 Ω m range, where the mode cut-off is unchanged, the structure can be used as a variable attenuator with very constant attenuation over the waveguide band.
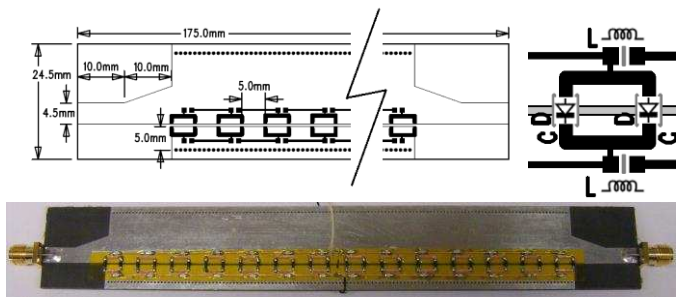

Fig 4. Structure of travelling wave attenuator

III. TRAVELLING WAVE ATTENUATOR

To demonstrate the variable attenuator, the structure shown in Fig. 4 was fabricated using Rogers RT5880. A 12 μm thick mylar overlay with 25 μm thick adhesive is placed over the waveguide to allow an array of twenty-eight BAR64-02 silicon pin diodes to be capacitively coupled to the waveguide slot in a similar manner to [5]. Each diode is separated by 5 mm with the bias applied across two thin tracks on the overlay. Inductors are embedded on the tracks to avoid coupling of the RF signal to the bias network. The diodes are connected to thick tracks that provide an approximate 2.5 pF capacitance between the pin diodes and each side of the slot. Tapered transitions to microstrip are used to enable the structure to be connected to SMA connectors for measurement.

Figure 5 shows measured results for the S-parameters of the structure obtained using an Anritsu network analyzer. The calibration was performed in coax and as such the SMA connectors are not de-embedded from the measurements. The measurements were performed for various bias levels ranging from a 30 V reverse bias to a 600 μA total forward current. The forward current shown in the figure is the total current through all 28 diodes and so the individual bias current will be the figure shown divided by 28. The pin diode data sheet did not provide data for resistance values at GHz frequencies but extrapolating the available low frequency values suggests an individual pin diode resistance of the order of a 5 kΩ (reverse bias) down to approximately 250 Ω (600 μA total forward bias current for all 28 diodes). From figure 2, this should give an attenuation of a few dBs up to approximately 30 dB for a 135 mm long section of loaded waveguide.

It is seen from figure 5 that the structure provides a constant variable attenuation from 2 dB to 25 dB over the waveguide band, which compares very well with that expected from figure 4. The attenuation drops below 2.7 GHz due to the cut-off of the mode. It also starts to fall off at 4.5 GHz, particularly for large values of attenuation. This is due to the resistance of the pin diodes falling with frequency and the effects of the other parasitic components of the diodes.
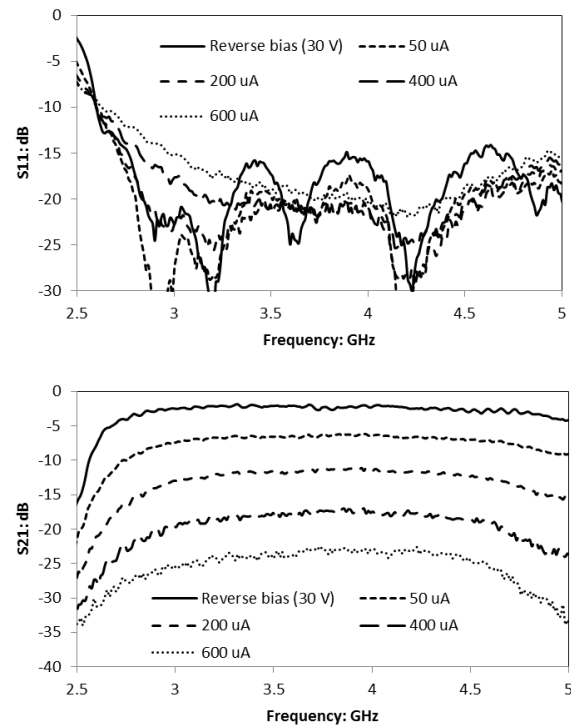

Fig. 5. Measured S-parameters of the variable attenuator structure given in Fig. 4 for various values of total forward current and reverse bias voltage.

IV. CONCLUSION

This letter has presented an approximate transverse resonance analysis of a periodically loaded slotted SIW. The technique has shown good agreement with full-wave solutions. The technique was further used to design a variable attenuator with good match and constant attenuation over a relatively wide bandwidth. The structure may find application for matching, power limiting and amplitude modulation applications particularly if scaled for millimeter-wave designs.

REFERENCES

[1] D. Deslandes and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," IEEE Microwave Wireless Compon. Lett., Vol. 11, no. 2, pp. 68-70, Feb. 2001

[2] D. Stephens, P. R. Young and I. D. Robertson, "Millimeter-wave substrate integrated waveguides and filters in photoimageable thick-film technology," IEEE Trans. Microwave Theory Tech., Vol. 53, No. 12, pp. 3822-3838, December 2005

[3] N. Grigoropoulos, B. Sanz Izquierdo, and P. R. Young, "Substrate integrated folded waveguide (SIFW) and filters," IEEE Microwave wireless compon. Lett., Vol. 15, No.12, pp.829-831, Dec. 2005.

[4] W. Hong, B. Liu, Y. Q. Wang, Q. H. Lai, and K. Wu, "Half mode substrate integrated waveguide: a new guided wave structure for microwave and millimeter wave application," in Proc. Joint 31st Int. Conf. Infrared Millim. Waves 14th Int. Conf. Terahertz Electron, Shanghai, China, Sep. 18-22, 2006, pp.219.

[5] Ruo Feng Xu, B. Sanz Izquierdo, and P. R. Young, "Switchable substrate integrated waveguide," IEEE Microwave wireless compon. Lett., Vol. 21, No. 4, pp.194-196, April 2011.

[6] D. M. Pozar, Microwave Engineering, 2nd Edition, John Wiley & Sons, Inc., 1998.

[7] Young Ki Cho, "On the equivalent circuit representation of the slitted parallel-plate waveguide filled with a dielectric," IEEE Trans. Antennas Propagat., Vol. 37, No. 9, pp. 1193-1200, September 1989