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A low-loss Ka-band waveguide to substrate integrated waveguide transition based on ridged stepped-impedance transformer

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A low-loss Ka-band transition from waveguide to substrate integrated waveguide (SIW) is presented based on ridge waveguide stepped-impedance transformer. This novel transition can operate across a full Ka-band (26.5 to 40 GHz) with an insertion loss lower than 0.59 dB and return loss over 14.2 dB. Furthermore, compared to existing transitions the introduction of ridges reduces the metal usage, resulting in weight reduction and offering an encouraging application for weight-sensitive satellite communications (SatComs).

Introduction: In recent years, mm-wave applications above 20 GHz have been increasingly playing a prominent role in the commercial development of Ka-band satellite communications (SatComs) and the fifth generation of mobile communications (5G). This has created an inexorable demand for components to meet stringent performance specifications at Ka-band and beyond. At these high frequencies, the losses related to planar/microstrip transmission lines are significantly higher than those at lower frequencies, and therefore air-filled waveguides are preferred solutions to reduce losses. However, most of the commercially available components are in the form of surface mount technology (SMT) or monolithic microwave integrated circuit (MMIC) technologies, requiring to be surface mounted, or wire bonded to a planar structure. To this end, efficient transitions from waveguide to planar technologies are desired to avoid unnecessary losses, especially in cost-sensitive applications such as SatComs, where just a few tenths of dB could result in a significant cost increase or even a system power shortage.

Substrate integrated waveguide (SIW) has provided a good solution at higher frequencies due to its low loss and easy integration with planar circuits, SMT components and MMIC chips. It also benefits from cheap fabrication costs and low profile. To synergise the strengths of air-filled waveguides and SIW, the transition between these two different structures is in great demand and several works have been reported in the literature [1–7]. However, the presented transition structures still suffer from large insertion losses (>0.8 dB) at Ka-band, which is intolerable in SatComs applications.

In this paper, a novel waveguide to SIW transition is presented based on a 4-stage ridged waveguide transformer. This transition provides an insertion loss lower than 0.59 dB over the entire Ka-band from 26.5 to 40 GHz. Additionally, it allows a reduction in manufacturing complexity by reducing the need of small diameter cutters (E-field is concentrated in the ridges), as well as reducing metal usage and weight compared to full-width transitions in [4].

Design: The 3D model of the proposed transition is shown in Figure 1. The design of the proposed transition begins by calculating SIW transmission line dimensions (Figure 2). For a standard SIW, the width depends on the substrate (dielectric constant ε_r), via diameter d and the pitch p between vias. The resulting SIW width is given by [8]

$$a_{siw} = W_{eq} + p\left(0.766e^{0.4485\frac{d}{p}} - 1.176e^{-1.214\frac{d}{p}}\right) \quad (1)$$

where W_{eq} is the effective waveguide width, calculated by

$$W_{eq} = \frac{c}{2f_c\sqrt{\epsilon_r}} \quad (2)$$

With the defined SIW dimensions, the waveguide to SIW transition is then designed based on a ridged stepped-impedance transformer. In this work, a four-stage transition is considered. Each stage consists of a

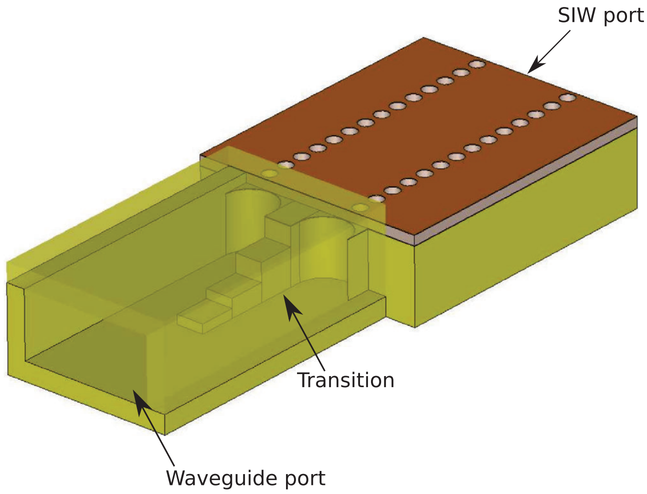

Fig. 1 *3D view of the proposed transition*

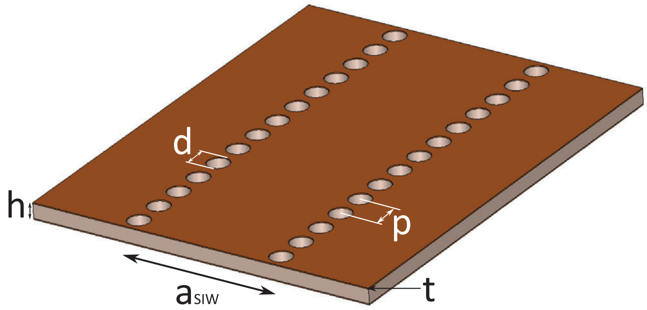

Fig. 2 *SIW geometry*

single-ridged step to create a progressive impedance transformation ratio. The geometric parameters of the design are given in Figure 3, where the longitudinal and cross-sectional views are illustrated. The principle of operation is matching the TE_{10} mode from the waveguide to the SIW by employing a multistage impedance transformation, which is a well-known technique in planar circuit design. To adapt to the height of the SIW, the last ridge height is given by

$$H_4 = b - h, \quad (3)$$

where b is the waveguide height and h is the SIW height. The rest of the heights are deployed to double the previous one and create the desired impedance transform ratio, so that

$$H_k = 2H_{k-1} \quad (4)$$

In addition, the ridge structure allows the use of bigger diameter cutters for the computer numeric control (CNC) manufacturing, thus reducing costs and tolerances in the zones with higher electric fields.

Simulated and measured results: For verification, a prototype has been designed and manufactured for Ka-band operation by using a standard WR-28 waveguide (7.112 mm × 3.556 mm). Simulations are carried out using commercially available CST software. The SIW is designed with the Rogers RF/Duroid 5880 substrate, where dielectric constant value $\varepsilon_r = 2.2$ and thickness $h = 0.254$ mm. Considering $d = 0.8$ mm and $p = 1.1$ mm (with $f_c = 21$ GHz), the width given by (1) is $a_{SIW} = 5.3$ mm, which is less than the width of the implemented waveguide, enabling the physical realisability. At the centre frequency (33 GHz) of the Ka-band the guided wavelength is $\lambda_g = 11.8$ mm. The initial ridge lengths are set to $L_k = 2.95$ mm (k is the stage number) and the width W of all the ridges is 1.5 mm.

After tuning and optimising for minimum insertion and reflection loss in the entire Ka-band, the resulting dimensions are shown in Table 1.

The photo of the manufactured prototype is presented in Figure 4, which consists of two transitions back-to-back. The measurements have

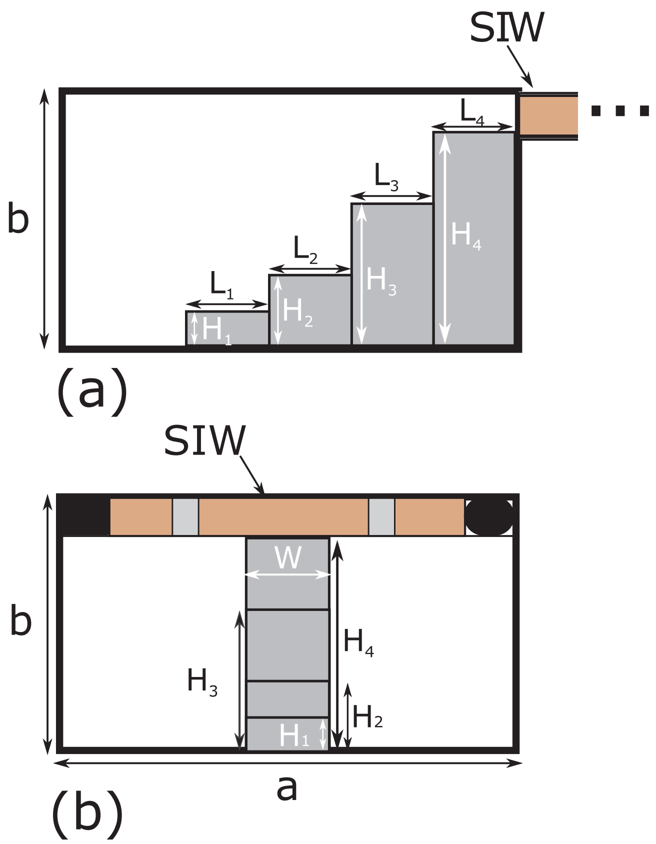

Fig. 3 *Dimensions of the design. (a) Longitudinal view. (b) Cross section*

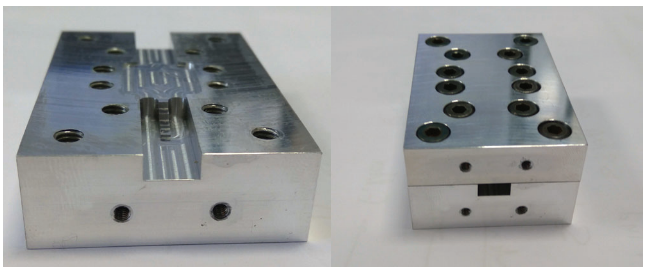

Fig. 4 *Photo of the manufactured back-to-back transition prototype*

Table 1. Final optimised parameters (all units in mm)

Ridge stage	1	2	3	4
H	0.5	1	2	3.046
L	2	2	2	2

been conducted with an Agilent N5225A network analyser and Figure 5 shows the experimental setup. The simulated and measured results are given in Figure 6. The measured insertion loss is lower than 0.59 dB and the return loss is higher than 14.2 dB over the entire Ka-band (26.5–40 GHz). Considering two transitions in a back-to-back configuration in the prototype, the resulting insertion loss for a single transition is lower than 0.295 dB. The discrepancy between measured and simulated results is mainly due to manufacturing tolerances. Furthermore, the performances of the proposed waveguide to SIW transition compared with others are summarised in Table 2.

Conclusion: In this paper, a low-loss waveguide to SIW transition based on a ridged stepped-impedance transformer has been proposed. The manufactured back-to-back prototype has an insertion loss lower than 0.59 dB and a return loss higher than 14.2 dB in the entire Ka-band. The employment of ridges in the transition not only achieves a lower insertion loss but also reduces the manufacturing tolerances as well as

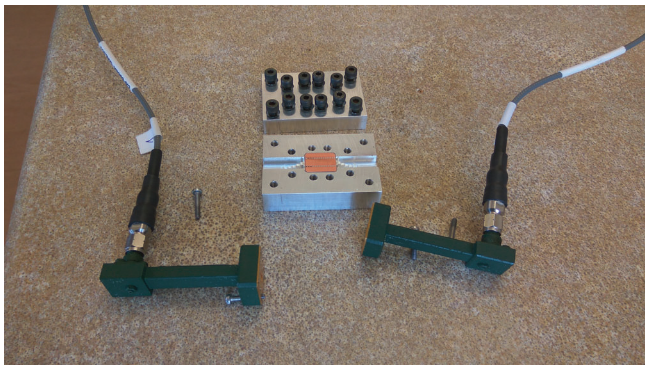

Fig. 5 *Setup for the measurement of the prototype*

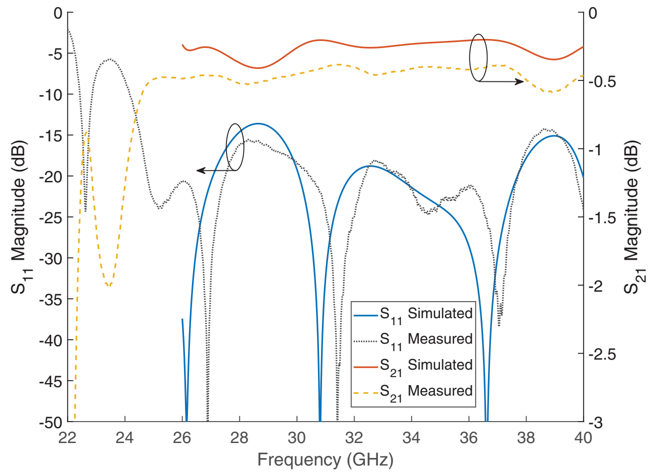

Fig. 6 *Simulated and measured results of the back-to-back structure*

Table 2. Comparison of waveguide to SIW transitions (back-to-back implementations)

	Freq. (GHz)	BW (%)	IL (dB)	RL (dB)
[1]	26.5–40	40.9	<1.1	>15
[2]	26.5–40	40.9	<1.4	>15
[3]	Centre at 26 GHz	6.6	<1.5	>15
[4]	32–50	45	<0.8	>15
[5]	28.3–39.5	33	<1.4	>14
[6]	34.2–35.3	3.2	<3.4	>11
This work	26.5–40	40.9	<0.59	>14.2

the weight of the metal material. Hence, the proposed waveguide to SIW transition provides a promising approach in SatComs applications.

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