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Plastic 95-GHz rectangular waveguides by micro molding technologies[☆]

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Abstract

A plastic, 95-GHz rectangular waveguide with an integrated plastic flange has been successfully demonstrated using micro hot embossing and electroplating technologies. Two prototype devices with integrated flanges on both ends have been tested using an *Agilent PNA* 5250 network analyzer. The prototype with non-metallized flange shows return loss s_{11} and insertion loss s_{21} values of -21.5 and -1.09 dB at 108 GHz, respectively with signal transmission rate at 77.8%. The prototype with metallized flange has s_{11} and s_{21} values of -31.5 dB and -0.7 dB, respectively, at 92.5 GHz, with signal transmission rate at 85%. The time domain measurement showed that the system losses are mainly due to the discontinuity losses at the interfaces between the network analyzer adaptors and the waveguide input/output ports. These losses could be further minimized in future integrated systems. As such, this new class of plastic waveguides has potential applications in replacing the expensive and bulky/heavy metallic waveguides in current millimeter-wave systems.

1. Introduction

Millimeter-wave sensor systems could provide various sensing functionalities for all-weather applications [1], such as automobile crash avoidance systems, airplane radars [2–4], astronomy, weather monitoring and soil/moisture sensing [5]. Metal rectangular waveguides are commonly employed for millimeter-wave systems because of their lower attenuation compared to microstrip or stripline structures [6]. Currently, rectangular waveguides are fabricated using conventional machining techniques in metal and later assembled/mounted to construct a complete millimeter-wave system. High frequency systems demand small feature sizes such that micromachining technologies are natural alternatives. Previously, Tai et al. have demonstrated a silicon-based rectangular waveguide using bulk micromachining processes of a ⟨1 0 0⟩-silicon wafer

with an insertion loss of 0.04 dB/λ for a frequency range of 75–110 GHz [7]. LeDuc et al. integrated a superconductor-insulator-superconductor (SIS) tunnel junctions mounted on a nitride membrane with a bulk micromachined rectangular waveguide fabricated using wet etching of a ⟨1 0 0⟩-silicon wafer. The waveguide was tested for a frequency range of 170–260 GHz and a 0.8 dB per wavelength insertion loss was measured [8]. Davies et al. have fabricated a reduced-height, air filled, surface-micromachined W-band rectangular waveguide. The waveguide performance was poor due to height limitation and the measured insertion loss was 0.2 dB/λ [9]. Katehi et al. demonstrated a diamond-shape waveguide in W-band using wet etching of a ⟨1 0 0⟩-silicon wafer and the mismatch between the WR-10 ports of the network analyzer and the diamond waveguide caused an insertion loss of 0.135 dB/λ [10].

This work presents a plastic, hot-embossed, W-Band waveguide. In contrast to the previous works, three distinctive achievements have been accomplished: (1) plastic waveguides using batch embossing technologies [11,12], (2) metallic coating and sealing by selective electroplating and bonding, and (3) integrating a precision hot-embossed flange using press fitting/instant glue bonding with subsequent planarization. We believe this new

technology provides the feasibility of low-cost manufacturing and integration with other micro electromagnetic-wave components, such as antennas, transmission lines, and phase-shifters for integrated millimeter-wave systems.

2. Theory and fabrication process

The cut-off frequency of a hollow metallic, air-filled rectangular waveguide could be found as [13]:

$$f_{c,mn} = \frac{1}{2\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad (1)$$

where $f_{c,mn}$ is the cutoff frequency, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, a is the width of the waveguide, b is the height of the waveguide, and m, n are integer numbers for the propagating modes. The desired fundamental mode in a rectangular waveguide is the transverse electric TE$_{10}$ mode ($m = 1$ and $n = 0$). It is desirable to have the operating frequency higher by 60% than the cut-off frequency of the mode and lower by 25% of the cut-on frequency of the next mode. For 95-GHz systems, the design conditions are:

$$1.6 f_{c,10} = 95\,\text{GHz} \quad \text{and} \quad 0.8 f_{c,01} = 95\,\text{GHz} \qquad (2)$$

and the dimensions of a W-band waveguide become 2.54 mm × 1.27 mm. For conventional millimeter-wave systems, the fabrication process of a waveguide/flange is typically done by precision machining on a metallic block followed by brazing a metallic cover to enclose the waveguide.

In the proposed plastic molding process as illustrated in Fig. 1 [14], an aluminum mold insert is fabricated by traditional mechanical machining and is used to pattern a plastic substrate to form an open waveguide using hot embossing at 320 °F. A tolerance of ±0.015 mm is required on the rectangular ridge of the mold. The mold is designed to process a plastic substrate with thickness of 2.5 mm and length of 25.4 mm. The plastic replica is then detached and subsequently a layer of 200 Å/6000 Å Cr/Pt is sputtered as the seed layer for the following electroplating step. A second silicon substrate is sputtered with 500 Å/6000 Å
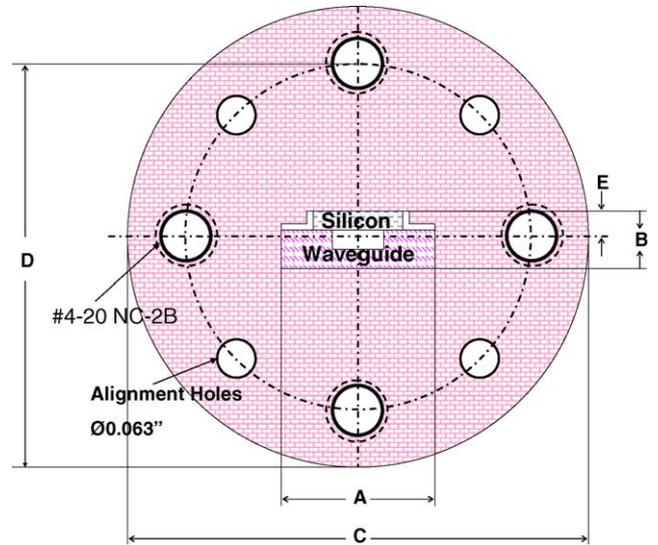
Fig. 2. A schematic diagram of the flange design showing how the waveguide with the silicon cap is press fitted and sealed. The dimensions A, B, C, D, and E are 10, 3, 19.1, 14.3, and 1.15 mm, respectively.

Cr/Pt combination and is clamped on top of the first substrate to cover the open waveguide. A flange adaptor is separately fabricated using the same hot embossing process in such a way that the open waveguide/silicon cover could be integrated with the adaptor to fit into the standard waveguide measurement instruments as shown in Fig. 2. Screw threads and pinholes are drilled at the precise locations with a tolerance of ±0.015 mm. The clamped combination of open waveguide/silicon cover is press fitted and glued using super glue (Loctite quicktite). The surfaces of the flange/press fitted waveguide are planarized using lapping with silicon carbide paper of very fine 600 grid mesh. The waveguide with integrated flange adaptor is then immersed into a gold electroplating solution (140 °F and 1000 rpm) to deposit an 8 μm-thick gold layer.

The selective electroplating process also metallically seals the waveguides [15]. Fig. 3 shows two SEM micrographs of the fabricated waveguide. From the preliminary observation, the
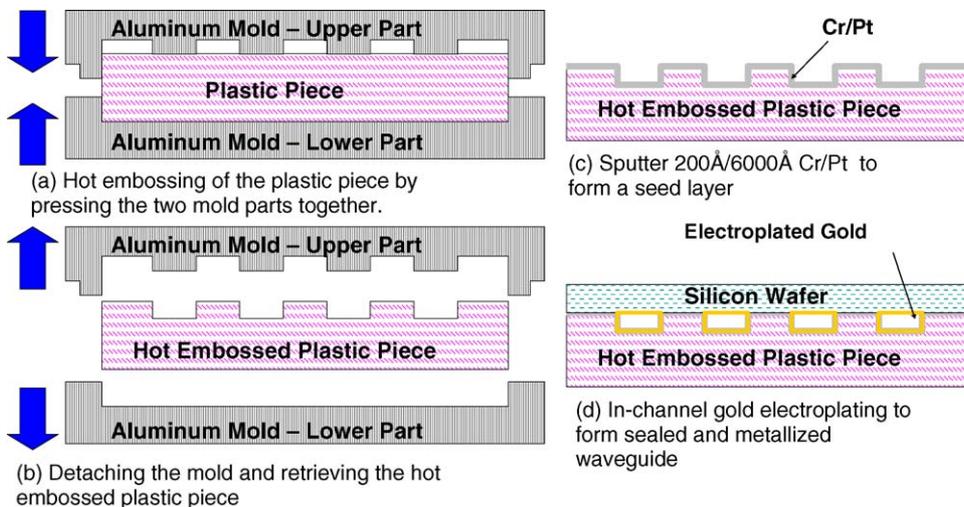
Fig. 1. Fabrication process of the waveguide.
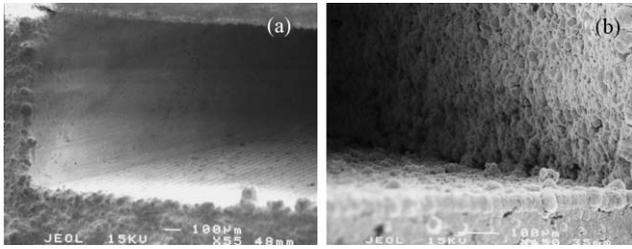
Fig. 3. SEM pictures of the waveguide. (a) The lower left corner of the waveguide and (b) close up view of the lower right corner showing good sealing between the 2 wafers.
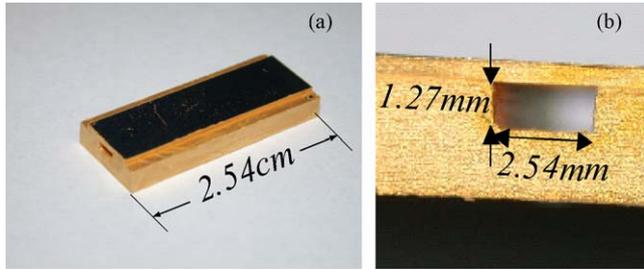
Fig. 4. (a) A photograph of the fabricated waveguide and (b) a close-up tilted view of the waveguide showing both the input and the output port.

metallic surface is smooth with a measured surface roughness using AFM [16] with RMS value of 1350 Å and the electroplated sealing is good with no observable leak. Fig. 4a is the photo of the fabricated waveguide that is 2.54 cm in length and Fig. 4b is the close-up tilted view of the waveguide showing both the input and the output ports. Fig. 5a is an optical photo of the prototype integrated with non-metallized flange adaptors at both ends and Fig. 5b is a close-up view of the flange showing the planner surface of the flange after the lapping process. Fig. 6 shows the photo of the prototype matallized flange sitting next to a conventional rectangular waveguide manufactured by Agilent Inc.

3. Results and discussion

The dimensions of the plastic 95-GHz rectangular waveguide were measured using a micrometer. The height and width of the waveguide are 1.295 mm and 2.515 mm, respectively. These
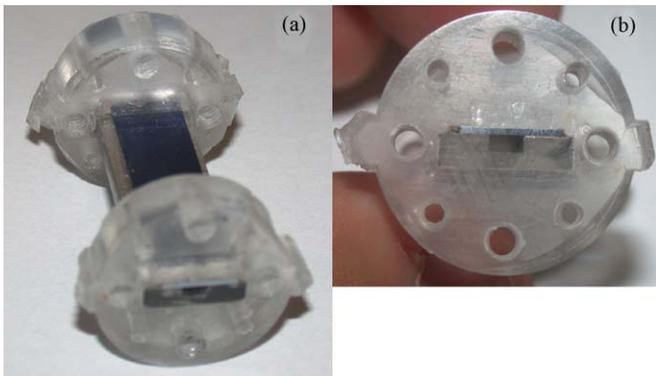
Fig. 5. Waveguide with non-metallized flange: (a) A photograph of the waveguide with integrated flange adaptors and no metallized flange walls; (b) a close up view at the flange adaptor.
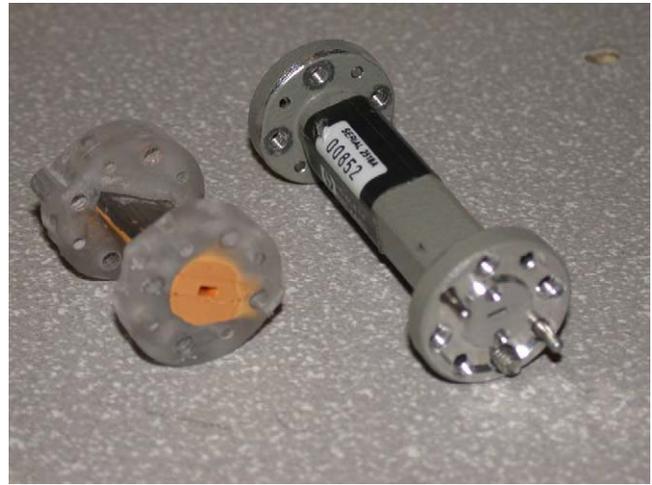
Fig. 6. Waveguide with metallized flange: (left) a microfabricated plastic 95 GHz waveguide with metallized flange; (right) a conventional metallic waveguide by Agilent Inc.

numbers fall within the acceptable tolerance of the guidelines of a standard metallic W-band waveguide that could allow for ±0.03 mm variation in the waveguide cross-sectional dimensions [17]. The variations could be attributed to the shrinkage of the plastic as well as inaccuracies of the mold itself (the mold variation was +0.012 mm and −0.01 mm in ridge height and width, respectively).

The scattering parameters s_{11} (indicating return loss) and s_{21} (indicating transmission loss) of the waveguide are measured from 75 to 110 GHz using *Agilent PNA* 5250 network analyzer shown in Fig. 7a. Fig. 7b shows a close up view of the waveguide connected to a network analyzer. Fig. 8 is the measured frequency response for the waveguide without metallized flange. It is noted that the s_{11} was between −20 and −40 dB between 75 and 110 GHz while the typical metallic waveguide can have responses less than −40 dB. The resonant nulls are due to the interfaces at each end of the waveguide. The insertion loss parameter s_{21} varies between −1.79 dB at 75 GHz to −1.06 dB at 110 GHz. At 95 GHz, the insertion loss is −1.35 dB and the return loss is −20.7 dB. The guided wavelength of the propagating wave inside a hollow, air-filled rectangular waveguide is a function of frequency and could be calculated as follows [13]:

$$\lambda_g = \frac{2\pi}{\sqrt{\omega^2 \mu_0 \varepsilon_0 - (\pi/a)^2}} \tag{3}$$

where λ_g is guided wavelength of the TE_{10} mode, ω is the radian frequency in rad./s, μ_0 and ε_0 are the permeability and permittivity of free space, respectively, and a is the width of the waveguide. It is calculated that at 95 GHz, λ_g is 4.03 mm and a waveguide length of 25.4 mm corresponds to 6.3 wavelengths. Thus the insertion loss per wavelength at 95 GHz becomes 0.214 dB/λ_g (0.531 dB/cm). This is larger than the nominal value of 0.026 ∼ 0.028 dB/cm in a commercial WR-10 single-mode metallic waveguide without connectors.

The relatively poor performance of the waveguide comes from the interface contact losses between the waveguide and the measurement apparatus. The time domain measurement in
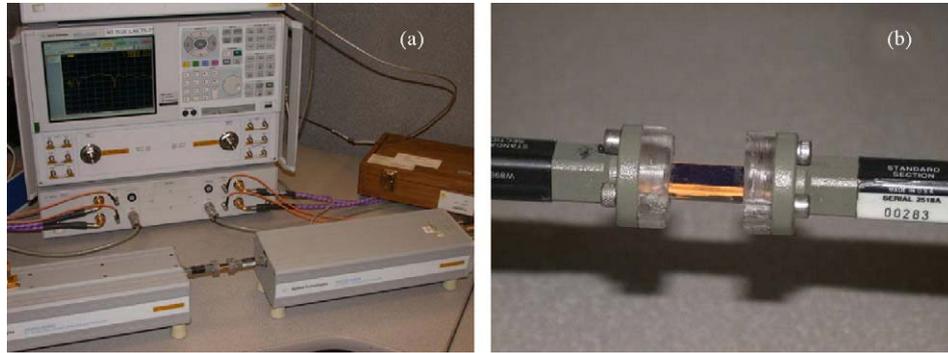
Fig. 7. Testing set-up. (a) *Agilent PNA* 5250 network analyser; (b) close up view of waveguide connected to a network analyser.
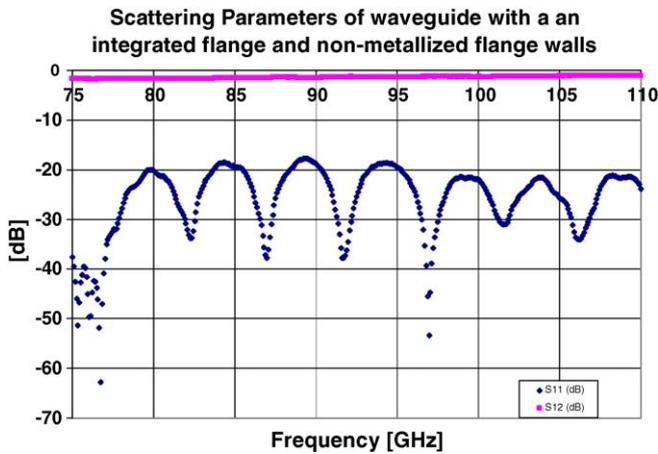
Fig. 8. Scattering parameters for the waveguide with non-metallized flange measured using *Agilent* network analyzer *PNA* 5250. At 95 GHz, the return loss parameter, s_{11}, is -20.7 dB and the insertion loss parameter, s_{21}, is -1.35 dB.

Fig. 9 verified this. The time domain plot of the return loss parameter s_{11} showing the major reflections are at the interfaces between the input/output port and the network analyzer adaptor. The peak at the point 1 shows the return loss at 0 s when the signal passes port 1, and the peak at point 3 shows the signal

reflected after 220 ps back from port 2. The small reflection in between comes from the waveguide itself. It is worth mentioning that a full trip of the wave from port 1 to port 2 and back to port 1 takes 220 ps. The group velocity, v_g, of a propagating wave with a single carrier frequency inside a hollow rectangular waveguide could be calculated as [13]:

$$v_g = \frac{\sqrt{\omega^2 \mu_0 \varepsilon_0 - (\pi/a)^2}}{\omega \mu_0 \varepsilon_0} \qquad (4)$$

The group velocity at 75 and 110 GHz is 1.85×10^8 and 2.53×10^8 m/s, respectively. The time required for a wave to make one trip from port 1 to port 2 of a waveguide of 25.4 mm in length varies from 100 ps at 110 GHz to 137 ps at 75 GHz. The 110 ps travel time measured from the network analyzers falls within this range. The difference between the theoretical and experimental data is due to the fact that in calculating the time domain data, the network analyzer uses *Inverse Fast Fourier Transform technique* (IFFT), which assumes a constant propagation constant within the 75–110 GHz frequency range.

Fig. 10 is a time domain plot of the transmission parameter s_{21}, showing that maximum transfer of energy occurs at point 2 after 110 ps, i.e. at the output interface. The loss is thus mainly concentrated at the input and output ports and is attributed to the small gap between the flange/waveguide connection the network analyzer adaptor due to the non-metallized flange surface.

Fig. 9. A time domain log-scale plot of the return loss parameter, s_{11}, showing the major reflection losses are at the interfaces between the input/output ports and the network analyzer adaptor. The peak at point 1 shows the return loss at 0 s (port 1), and the peak at point 3 shows the return loss after 220 ps (port 2). The small reflection in between comes from the waveguide itself.

Fig. 10. A time domain log-scale plot of the insertion loss parameter, s_{21}, showing the maximum transfer of energy occurred at point 2 after 110 ps (when the wave arrives at port 2).
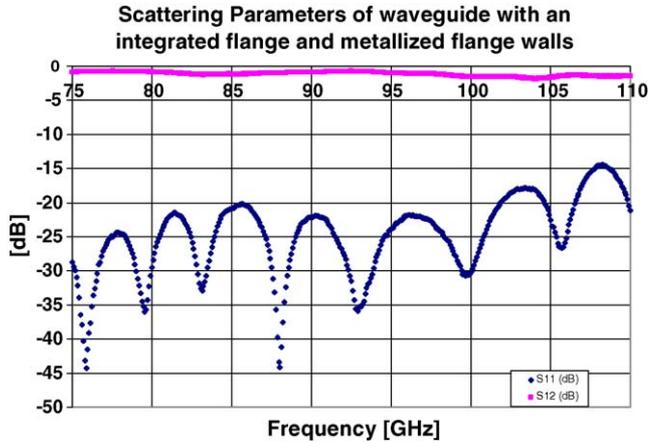
Fig. 11. Scattering parameters of the waveguide with metallized flange measured using *Agilent* network analyzer PNA5250. At 95 GHz, the return loss parameter, s_{11}, is -24.5 dB and the insertion loss parameter, s_{21}, is -0.96 dB. At 92.5 GHz, s_{11} is -31.5 dB and s_{21} is -0.7 dB (85% transmission).

This issue can be resolved in an integrated system where all the connection interfaces are integrated and fabricated at the same time.

In order to reduce the interface contact losses between the waveguide and the measurement apparatus, the surface of the flanges in contact with the network analyzer adaptors was metallized. The scattering parameter results for the waveguide with metallized flanges are shown in Fig. 11. The best performance was measured at 92.5 GHz: the return loss s_{11} was -31.5 dB and the insertion loss s_{21} was -0.7 dB and the insertion loss per wavelength is 0.116 dB/λ_g (0.276 dB/cm). At 95 GHz the s11 and the s21 values were -23.9 and -0.99 dB, respectively, and the insertion loss per wavelength is 0.157 dB/λ_g (0.39 dB/cm).

For a reciprocal ($[S_{ij}]=[S_{ij}]^*$) and no loss network, one has [18]:

$$\sum_{k=1}^{N} s_{ki}s_{ki}^* = 1 \tag{5}$$

For a two-port network, Eq. (5) becomes:

$$|s_{11}|^2 + |s_{21}|^2 = 1 \tag{6}$$

Whenever the summation of transmission and return losses does not add up to the unity, there is dissipation within the system. The dissipation is mainly due to imperfectly reflecting walls. The attenuation factor α_c could be theoretically calculated as follows [18]:

$$\alpha_c = \frac{P_{\text{loss}}}{2P_{\text{total}}} = \frac{R_s}{a^3 b\beta\omega\eta\sqrt{\mu_0\varepsilon_0}}(2b\pi^2 + a^3\omega^2\mu_0\varepsilon_0)\left[\frac{Np}{m}\right] \tag{7}$$

where R_s is the sheet resistance of the waveguide surface, a and b are the width and height of the waveguide, respectively, β is the propagation constant, ω is the frequency, μ_0 and ε_0 are the permeability and permittivity of free space, respectively. The measured conductivity of the electroplated film using a four point probe was 1.5×10^6 /Ω m. Fig. 12 compares the attenuation coefficient, α_c, versus frequency for both experimental and theoretical data. The experimental attenuation coefficient is obtained with the interface losses since we cannot separate them
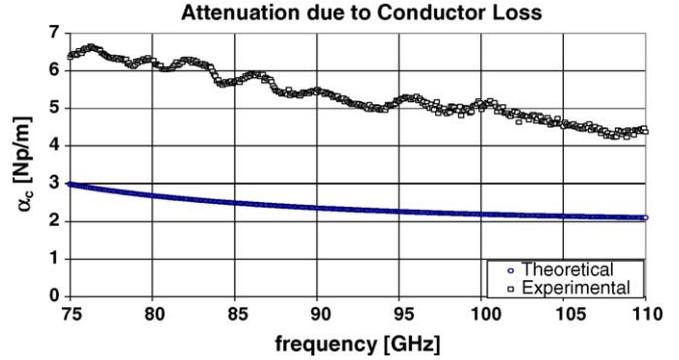
Fig. 12. Experimental and theoretical attenuation due to conductor loss vs. frequency.

form our measurement. The two plots follow the same trend of decreasing attenuation coefficient versus frequency. The difference between theoretical and experimental values is due to other unaccounted losses such as dielectric losses as well as signal leakage/radiation at the input/output interfaces.

4. Conclusion

Plastic 95-GHz rectangular waveguides have been demonstrated. The waveguide has been batch fabricated using inexpensive hot embossing and electroplating techniques. Two prototype waveguides with integrated flanges on both sides have been tested walls using an *Agilent PNA* 5250 network analyzer. The measured scattering parameters s_{11} (return loss) and s_{21} (transmission loss) from 75 to 110 GHz for the first prototype without a metallized flange show minimum insertion loss of -1.06 dB at 109.6 GHz, which corresponded to 0.129 dB/λ_g. The performance was further improved by fixing the discontinuity between the waveguide itself and the network analyzer cable adaptors by metallizing the flange surface. The measured scattering parameters s_{11} and s_{21} for the second prototype with a metallized flange show improvement as minimum insertion loss of -0.7 dB at 92.5 GHz, which corresponded to 0.116 dB/λ_g. The attenuation coefficient due to conductor losses was also calculated and compared to theoretical predictions. An attenuation of 5.2 Np/m was measured at 95 GHz compared to 2.3 Np/m predicated from theory. The discrepancy is again due to the measurement interface. It is envisioned that this new class of waveguides could facilitate the integration of other millimeter-wave components such as antennas, filters [19], and phase shifters toward an integrated system.

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