

Elliptical Chokes Operating in Full WR-3 Band

Yusa Takemoto, Shigenori Mattori

[Summary]

The WR-3 band (220 to 330 GHz) in the sub-THz wave band is expected to be used for wireless communication because it is relatively unaffected by atmospheric attenuation. Switches with mechanically sliding waveguides are used for low-loss signal switching in these high-frequency bands but electromagnetic waves leak from the mechanical switch parts. Chokes covering the fully operating band of standard waveguides would be useful for suppressing this leakage. Four elliptical choke designs (simple, non-split, split, and flat type), which operate across the full WR-3 band, were investigated and their effectiveness was demonstrated by simulation and actual measurements. Simulations compared changes in transmission loss due to waveguide misalignment, showing that the split elliptical choke in particular is less susceptible to the effects of waveguide misalignment. However, the split elliptical choke suffers larger leakage loss of ≤ 14 dB compared to the other three types of elliptical chokes, and finding a more effective solution remains a challenge for future research.

1 Introduction

There are high hopes for the 300 GHz band, which can achieve transmission speeds of tens of Gbps to support future increases in mobile data traffic. The WR-3 band (220 to 330 GHz) within these frequencies is expected to be used for wireless communication because atmospheric attenuation due to oxygen molecules and water vapor in the atmosphere absorbing radio waves is less than 10 dB/km^1 making WR-3 best suited to wireless applications. In response, basic R&D into spectrum measurements is examining use of the WR-3 band for wireless communications²⁾. This research has resulted in the development of a waveguide filter bank by switching between multiple bandpass filters covering part of the WR-3 band (255 to 315 GHz) as a preselector for a spectrum measurement system³⁾. This filter bank is configured to switch between filters using 8 movable sliding waveguide filters arranged between the input and output waveguides. To prevent mechanical wear, the input and output waveguides and waveguide filters are not in contact and rectangular chokes are installed on opposing surfaces across the gap. Although chokes can effectively suppress transmission losses by reducing electromagnetic wave leakage from the gap at the connection point⁴⁾, chokes narrow the operating bandwidth according to the width of the gap (g)⁵⁾. While the referenced³⁾ chokes secured transmission losses of less than 0.1 dB and isolation of more than 50 dB even at gap width of 0.1 mm, the usable bandwidth was limited to 255 to 325 GHz,

from a practical standpoint it is better to use chokes supporting the full operating bandwidth of standard waveguides. It is difficult to reduce the gap in mechanical waveguide switches to less than 20 or 30 μm due to constraints imposed by machining precision, sliding friction, and wear. However, the ratio of the gap to the wavelength becomes larger as the frequency increases, making it more difficult to fabricate chokes operating over a wide bandwidth. Moreover, keeping any misalignment between waveguides below a few μm is difficult and the impact of misalignment becomes greater at higher frequencies. Additionally, the referenced³⁾ waveguide filter bank has chokes at both sides of the connection, but it is better to install chokes on only one side from the manufacturing cost perspective. Based on these ideas, this study examined chokes for the WR-3 band meeting the following conditions: (1) full-band operation, (2) high tolerance to waveguide misalignment, and (3) one-sided choke configuration.

Rahiminejad *et al.* has described⁶⁾ a non-contact gap adapter installed on one side of the waveguide connection and satisfying the requirements of (1) and (3) above. It is a circular waveguide connection structure that suppresses leakage between flange surfaces using a periodic structure developed by Kildal *et al.*⁷⁾ and is manufactured using SU8 polymer. While the design has good transmission characteristics in the 220 to 325 GHz operation range with a gap ($g = 0.05 \text{ mm}$), the manufacturing process is complicated, and there are concerns about aging deterioration of the polymer material.

With respect to requirement (2), the egg-shaped choke flange described by Pyne *et al.*⁽⁸⁾ is reported to have no significant change in operating bandwidth due to parallel and angular misalignment of the connected waveguides. While the effect of misalignment is small, the operating bandwidth for $g = 0.5$ mm (approximately $1/50$ wavelength) is 8.5 to 11 GHz, which covers only about 75% of the full WR-90 band (8.2 to 12.4 GHz). Therefore, using the referenced choke⁽⁸⁾ for the WR-3 band would probably not cover the full bandwidth even with a gap ($g = 0.02$ mm).

This article reports our investigation into four new elliptical chokes that operate across the entire WR-3 band when installed only on one side of the connection with $g = 0.05$ mm (approximately $1/20$ wavelength). We focus on the WR-3 band where gap effects are significant and describe numerical analysis results in actual dimensions and real frequencies for intuitive understanding. The results can also be discussed as general theory by normalizing with the waveguide cutoff wavelength or cutoff frequency. Unless stated otherwise, the numerical analysis ignores conduction losses.

2 Elliptical Choke Basics

2.1 Proposed Simple Elliptical Choke

Figure 1(a) shows a general model with a gap ($g = 0.05$ mm) between flat flanges connecting two waveguides. Electromagnetic waves leak between the flanges as shown in Figure 1(b) when there is no choke groove. This example shows the results of harmonic analysis using an electromagnetic field simulator (Femtet, Murata Software Co., Ltd.) to model the opposing flange faces of a standard WR-3 waveguide (0.864×0.432 mm). Harmonic analysis drives a sine wave from a set oscillation source and analyzes the frequency response characteristics of the model to that sine wave. Figure 1(b) shows the z -direction electric field intensity at a frequency of 280 GHz. The red solid line indicates where the z -direction electric field intensity is zero, representing lines of equal phase. The power of leaking electromagnetic waves is almost circular at distances more than one wavelength from the waveguide opening, but the shape is closer to an ellipse near the waveguide. Based on the results in Figure 1, it seems natural to use an elliptical choke groove as the prototype. The leakage power from the gap is defined by Eq. (1), and the leakage loss is defined by Eq. (2). Figure 1(c) shows

the transmission loss $|S_{21}|$ and leakage in the WR-3 band, where the leakage loss is ≤ 10 dB across the entire WR-3 range, meaning $\geq 10\%$ of the power leaks out.

$$\text{Leakage} = 10 \log_{10}(1 - |S_{11}|^2 - |S_{21}|^2) \quad (\text{dB}) \quad (1)$$

$$\text{Leakage loss} = -\text{leakage} \quad (\text{dB}) \quad (2)$$

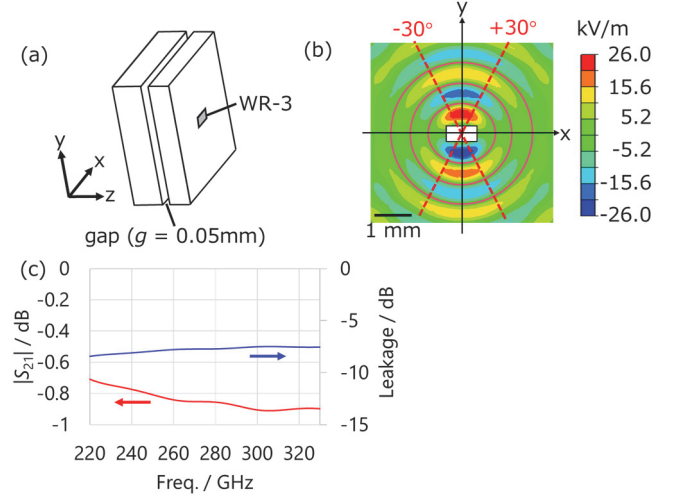


Figure 1 Leakage of electromagnetic field between flat flanges with gap ($g = 0.05$ mm) (a) Shape of harmonic analysis model, (b) Z -direction electric field strength without choke (WR-3, 280 GHz) (red solid line: Z -direction electric field strength = 0, red dotted line: position at $\pm 30^\circ$ from y -axis), (c) $|S_{21}|$ and leakage

2.2 Characteristics of Simple Elliptical Choke

This section outlines the choke principle (Figure 2). A groove with a length of one quarter of the wavelength perpendicular to the incident wave acts as a choke. Reflection at the short-circuited bottom of the groove reverses the phase of the electric field. Viewed from the incident side at the branch, the phase of wave 1 reflected at the bottom of the groove and returning to the branch, becomes in-phase with the incident wave. Conversely, viewed from the direction of the electric field, reflected wave 2 on the emission side becomes out-of-phase with the incident wave, so the two cancel each other out, suppressing leakage to the emission side.

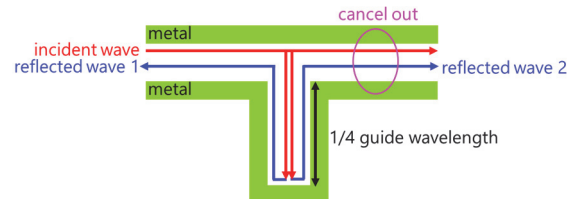


Figure 2 Choke principle

Chokes are inherently narrow bands because they prevent transmission through interference, so achieving wideband

operation requires investigation of conditions by the simulation. Using harmonic analysis of simple elliptical choke groove parameters for inner major radius (a), minor radius (b), groove width (w_c), and depth (h), and setting h to approximately $1/4$ of the guided wavelength suppresses power leakage to the outside from the choke groove over the entire WR-3 operating band. Moreover, the resonance frequency spacing (described later) becomes wider as the space surrounded by the waveguide opening and the inner wall of the choke groove becomes narrower. However, for machining, it is necessary to maintain a width of at least 0.1 mm. In practice, a transmission loss of ≤ 0.2 dB and leakage loss ≥ 15 dB were obtained at frequencies below 320 GHz as shown in Figure 3(b) when harmonic analysis of a simple elliptical choke was performed for $g = 0.05$ mm with the dimensions shown in Figure 3(a). This result shows that an elliptical choke can suppress electromagnetic wave leakage over a wide bandwidth. However, the transmission loss and leakage loss deteriorate near 324 GHz, which is insufficient for operation across the entire WR-3 band. The cause of the deterioration is described below. Since the distance from the waveguide opening to the near end of the choke groove is set to less than $1/4$ of the guided wavelength, the electric field entering the gap has almost uniform intensity in the radial direction and can be considered to propagate along the waveguide opening. In other words, since the gap near the waveguide opening of the simple elliptical choke can be considered as a ring-shaped transmission line surrounding the opening, resonance may occur in this ring. In fact, the calculated localized electric field intensity distribution around the opening suggests the possibility of resonance in the gap area at 324 GHz (Figure 3(c)).

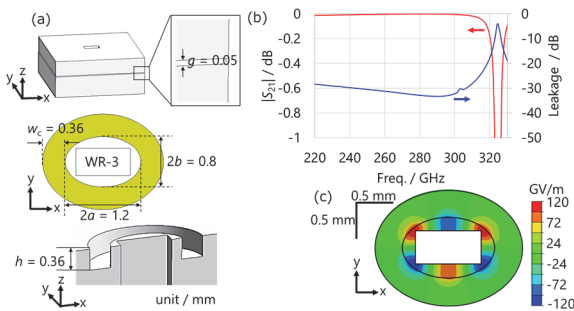


Figure 3 Harmonic analysis results for simple elliptical choke (a) Shape of analysis model, (b) $|S_{21}|$ and leakage, (c) Z-direction electric field intensity distribution at 324 GHz

2.3 Simple Resonance Analysis Model

To analyze resonance in the simple elliptical choke discussed in the previous section, we modeled the choke structure space, including the gap between the waveguide opening and the choke groove. Resonance analysis analyzes the model natural frequencies and natural vibration modes. Since the far end of the choke groove can be considered an electric wall and the extension plane of the waveguide inner wall can be considered a magnetic wall, we used a simplified resonance analysis model around the gap portion (Figure 4(a)). The electric field entering the gap is at opposite phases on both sides of the waveguide cross-sectional long edge (+y side and -y side) due to TE₁₀-mode propagation in the waveguide. Therefore, resonance in the gap is limited to cases where the direction of the electric field is antisymmetric with respect to the xz plane, and symmetric with respect to the yz plane. Only the mode at 317 GHz within the WR-3 band satisfies this condition, showing good agreement with the 324 GHz harmonic analysis result. Figure 4(b) shows the z-direction electric field intensity distribution at 317 GHz.

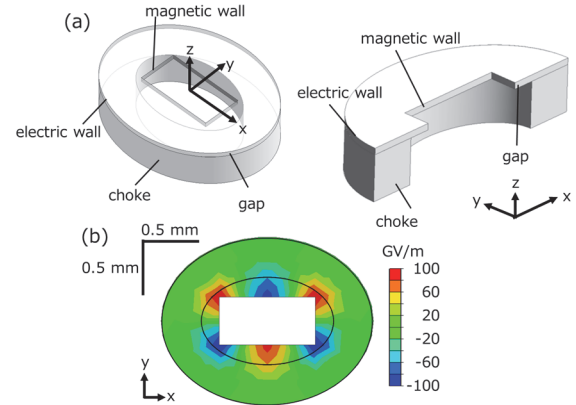


Figure 4 Simple elliptical choke resonance analysis results (a) Analysis model, (b) Z-axis (direction) electric field intensity distribution at 317 GHz

3 Structure of Suppressed-Resonance Elliptical Choke

As described in the previous section, resonance within the WR-3 operating band is a limiting factor for wideband operation. Three approaches to avoid the impact of resonance are:

- (1) Non-split elliptical choke: Provides open stub protruding into choke groove from near end of choke groove at waveguide opening, moving resonance frequency to lower range than operating band

- (2) Split elliptical choke: Creates ridge waveguide to divide choke, suppressing resonance by opening space where resonance occurs
- (3) Flattened elliptical choke: Narrows space resonance space to move resonance frequency to higher range than operating band

3.1 Non-Split Elliptical Choke

Short branch lines called stubs are added to a transmission line to add parallel impedance to the transmission line for load matching, among other applications. Installing stubs (Figures 5 to 7) in the gap of a simple elliptical choke might change the propagation conditions in the circumferential direction to significantly shift the resonance frequency. Figure 5 shows the resonance frequencies of each mode when a stub with width $w_s = 0.1$ mm and length $d = 0.155$ mm is placed in the waveguide opening plane in the direction angle θ . Distance d is the distance between A and B in Figure 5(a), showing the case where it is about half the width of the groove (w_c). However, the stub width (w_s) is set to be thin and within the mechanical processing constraints mentioned in section 2.2. The red, blue, and green circles in Figure 5(b) are calculated values and the solid lines are lines that complement these circles. There are only three resonances below 400 GHz excited in the gap by the waveguide TE₁₀ propagation mode: red: mode 1, blue: mode 2, and green: mode 3, and only mode 2 is within the WR-3 band. Resonance analysis shows that the resonance frequencies represented by the red, blue, and green graphs are consistent with the hollow circles and squares obtained by harmonic analysis. When a stub is placed along the diagonal direction of the waveguide ($\theta = 26.5^\circ$), the difference in resonance frequency between mode 2 and mode 3 is maximum at 138 GHz. While mode 2 is within the WR-3 band, the interval between the resonance frequencies of modes 2 and 3 is sufficiently wider than the WR-3 band's operating bandwidth (110 GHz), so it may be possible to cover the full WR-3 band by changing other shape parameters.

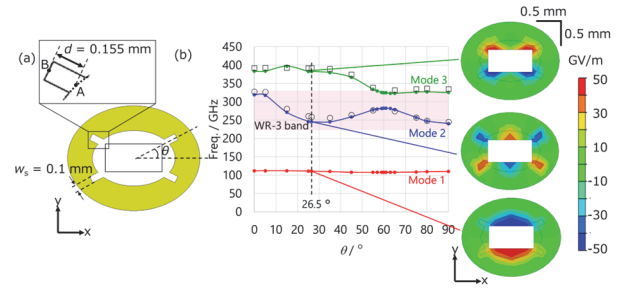


Figure 5 Resonance frequency vs stub angle ($d = 0.155$ mm) (a) Resonance analysis model, (b) θ dependence of resonance frequency and z -direction electric field strength of modes 1 to 3 ($\theta = 26.5^\circ$) (red: mode 1, blue: mode 2, green: mode 3; open circles and squares: resonance frequencies obtained from harmonic analysis)

Figure 6 shows the results of analyzing the resonance frequencies of each mode with respect to d when θ is fixed to 26.5° . Figure 6 confirms that the mode-2 resonance frequency decreases as d increases. In particular, when $d > 0.24$ mm, neither mode 2 nor mode 3 resonates within the WR-3 band.

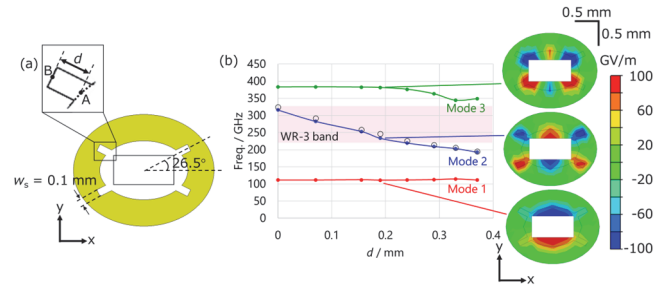


Figure 6 Resonance analysis results with stub ($\theta = 26.5^\circ$) (a) Resonance analysis model, (b) d dependence of resonance frequency and z -direction electric field strength of modes 1 to 3 ($d = 0.19$ mm) (red: mode 1, blue: mode 2, green: mode 3; open circles: resonance frequencies from harmonic analysis)

Therefore, as shown in Figure 7(a), we devised a structure where the outer surface of the choke groove protrudes near the stub, and the stub is further extended. Figure 7 shows the search results including this configuration for the shape parameters of the non-split elliptical choke to maximize the frequency range in which electromagnetic wave leakage can be suppressed. Specifically, we searched for the values of a , b , w_c , w_s , the width of the protruding wall section in the choke (w_{sc}), d , and the distance (d_{sc}) between A and C in Figure 7(a) of the non-split elliptical choke groove when $g = 0.05$ mm, $h = 0.36$ mm, and $\theta = 26.5^\circ$. The harmonic analysis results for the shape in Figure 7(a) showed transmission loss of ≤ 0.1 dB and leakage loss of ≥ 22 dB at 220 to 330 GHz (Figure 7(b)).

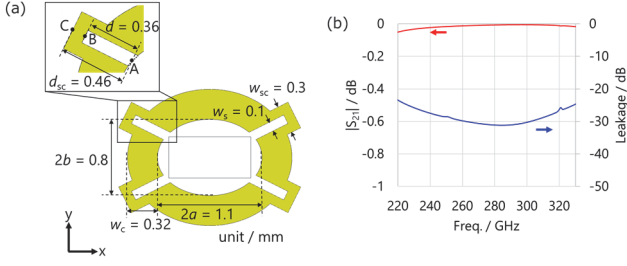


Figure 7 Non-split elliptical choke harmonic analysis results (a) Shape of analysis model, (b) $|S_{21}|$ and leakage

3.2 Split Elliptical Choke

When the stub is extended outside the choke groove, the formed ridge waveguide divides the choke groove. As a result, even if resonance occurs in the gap near the waveguide, resonance should be suppressed by leakage to the outside the choke groove. Therefore, while split elliptical chokes increase leakage compared to non-split elliptical chokes, they are less likely to produce strong resonances that would inhibit wideband operation. Here it is called a split elliptical choke because the choke groove is divided into four parts. We searched for shape parameters a , b , w_c , and w_s that would maximize the frequency range in which electromagnetic wave leakage can be suppressed when $g = 0.05$ mm, $h = 0.36$ mm, and $\theta = 26.5^\circ$. For the shape shown in Figure 8(a), harmonic analysis results with transmission loss of ≤ 0.2 dB and leakage loss of ≥ 14 dB were obtained in the 220 to 330 GHz range (Figure 8(b)).

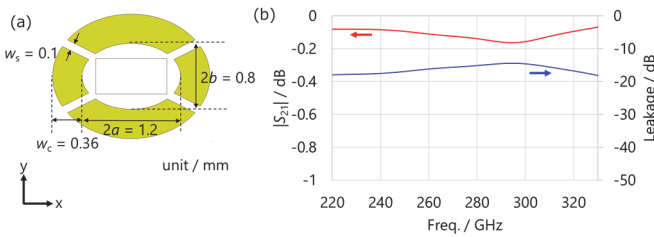


Figure 8 Split elliptical choke harmonic analysis results (a) Shape of analysis model, (b) $|S_{21}|$ and leakage

Despite the expectation that the split portion of the opposing flange surfaces would function as a transmission line, the following points explain why electromagnetic wave leakage loss was suppressed to 14 dB or more across the entire WR-3 range. As shown by the red dotted line in Figure 1(b), the electromagnetic waves leaking into the gap radiate with strong electric fields in the range of approximately $\pm 30^\circ$ from the y-axis when viewed from the center of the waveguide. Therefore, we think that electromagnetic wave leakage is suppressed effectively by having the split elliptical choke

cover the y-axis region where the electric field radiates strongly.

3.3 Flat Elliptical Choke

Obviously as the volume of the resonator becomes smaller, the resonance frequency becomes larger. Therefore, by making the space from the waveguide opening to the choke groove smaller than the simple elliptical choke, the resonance at 324 GHz should shift to the higher frequency side. To achieve this, we designed a flat elliptical choke that shortened the short side of the waveguide cross-section and made the elliptical choke flatter. A shortened waveguide with reduced short sides can be connected to a WR-3 standard waveguide with suppressed reflection using an adapter. The conversion loss at the connection increases as the size difference between the waveguides becomes larger. On the other hand, the resonance frequency increases as the space from the waveguide opening to the inside of the choke groove is narrowed. Considering this tradeoff, we simultaneously explored the shape parameters of the waveguide short side and the flat elliptical choke to design a resonance frequency of ≥ 330 GHz when $g = 0.05$ mm, with a minimum machining width of 0.1 mm. As a result, we obtained a waveguide short side of 0.2 mm and the values of a , b , and w_c shown in Figure 9(a). Analysis results for this shape, gave a transmission loss of ≤ 0.1 dB and a leakage loss of ≥ 25 dB or more in the 220 to 330 GHz range (Figure 9(b)).

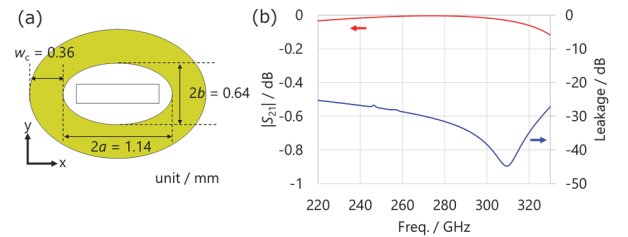


Figure 9 Flat elliptical choke analysis results (a) Shape of analysis model, (b) $|S_{21}|$ and leakage

4 Multiplexing Elliptical Chokes

Figure 10 shows the leakage harmonic analysis results for single, double, triple, and quadruple elliptical chokes. The four types of multiple elliptical chokes are based on the single choke shown in Figures 3 and 7 to 9, and are made into multiple structures by providing choke grooves with the same aspect ratio. The non-split elliptical choke shown in Figure 10(b) has stubs only in the innermost elliptical choke

groove, while the double to quadruple parts have simple elliptical choke grooves. For multiple chokes, the thickness of the wall (w_w) separating the choke grooves was set at 0.12 mm, considering the technical constraints of machining and the strength of the material. It was confirmed that the simple, non-split, and flat quadruple elliptical chokes shown in Figures 10(a), (b), and (d), respectively, have decreased leakage as the number of choke grooves increased. However, in the multiple split-type elliptical choke shown in Figure 10(c), the stubs dividing the choke grooves function as ridge waveguides, and no dependence of leakage on the number of choke grooves was observed, especially above 310 GHz. Additionally, complex resonances occur with multiplication of choke structure.

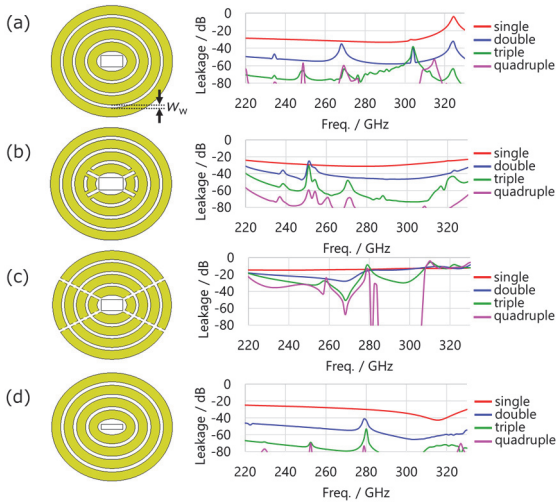


Figure 10 Leakage harmonic analysis results for single, double, triple, and quadruple elliptical chokes: (a) Simple elliptical quadruple choke, (b) Non-split elliptical quadruple choke, (c) Split elliptical quadruple choke, (d) Flat elliptical quadruple choke

5 Elliptical Choke Test Results

This section presents the measured results for simple, non-split, split, and flat elliptical chokes. Based on the multiple-choke harmonic analysis results in the previous chapter, tested (DUT) simple, non-split, and flat elliptical chokes used a quadruple choke structure that secures sufficient leakage loss of 50 dB with only a single-sided choke. On the other hand, the split elliptical choke was made as a single structure. For comparison, a waveguide without a choke was also prepared as a reference DUT.

Each choke was fabricated by machining aluminum alloy

(A6061). Measurements were performed using a DUT formed by connecting a waveguide with a choke and a waveguide with a protrusion, as shown in Figure 11(a). Each corner of the flange surface of the waveguide with the protrusion had a 0.05 mm high protrusion (right side of Figure 11(a)), so the g equals 0.05 mm when connected to a waveguide with or without a choke. The length of each waveguide was set to 59 mm (Figure 11(b)). Measurements were made using a vector network analyzer connected to a WR-3 band frequency extender. The DUT with a flat quadruple elliptical choke was connected to the WR-3 flat flange of the frequency extender through a 4-stage Chebyshev type adapter. DUTs with simple quadruple elliptical choke, non-split quadruple elliptical choke, and split elliptical choke were connected directly.

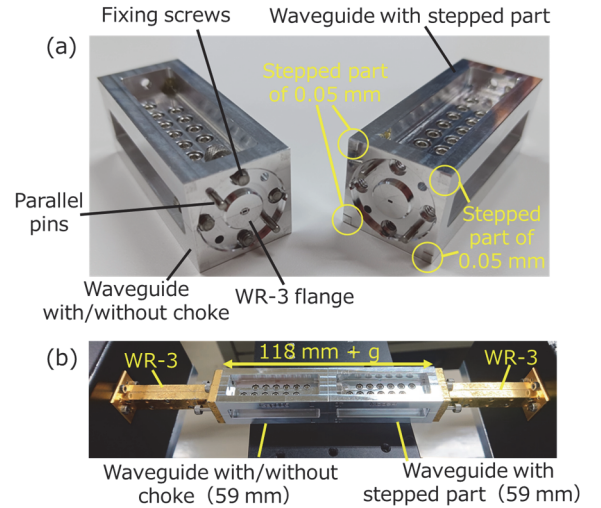


Figure 11 Test Setup (a) External appearance of waveguide with/without choke (left) and waveguide with protrusion (right), (b) Connection of waveguide with/without choke and waveguide with protrusion, and connection to WR-3 flange of frequency extender

Figure 12 shows the $|S_{21}|$ harmonic analysis and measured results for four types of elliptical choke with waveguide connection where $g = 0.05$ mm. The simulation values consider the aluminum alloy conductor loss, and the calculations assume a perfectly smooth surface. The difference between simulated and measured values was 0.5 to 1.2 dB for all elliptical choke types. For example, the difference was 0.8 dB at 275 GHz in the middle of the WR-3 band for the non-split elliptical choke. This difference is thought to be because the analysis did not account for surface roughness.

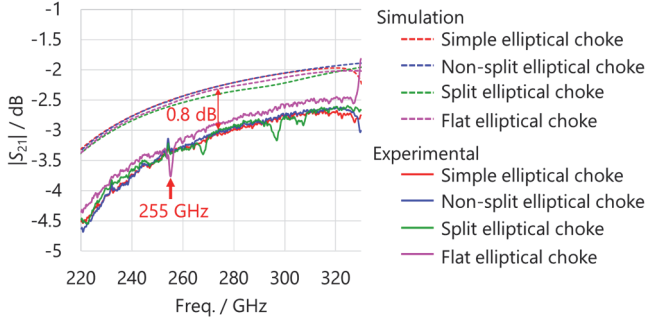


Figure 12 $|S_{21}|$ harmonic analysis and measured results for simple quadruple elliptical choke, non-split quadruple elliptical choke, split elliptical choke (single), and flat quadruple elliptical choke ($g = 0.05$ mm)

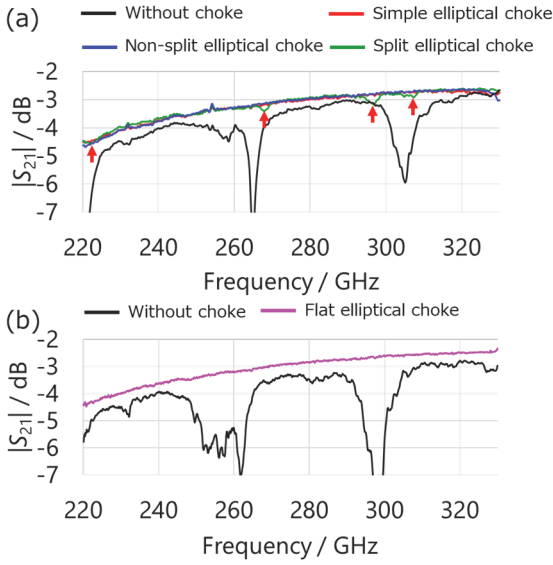


Figure 13 $|S_{21}|$ measured results for DUT and reference DUT ($g = 0.05$ mm) (a) Simple quadruple elliptical choke, non-split quadruple elliptical choke, split elliptical choke (single), (b) Flat quadruple elliptical choke

Figure 13 shows the measured $|S_{21}|$ values when connecting the DUT (simple, non-split, split, flat) to the WR-3 flat flange and elliptical choke waveguide and for the reference DUT connected to the WR-3 flange. An increase in $|S_{21}|$ of about 0.5 to 5 dB compared to the reference DUT (solid black line) was observed across the full WR-3 range in all choke structures, indicating that electromagnetic wave leakage was successfully suppressed.

6 Effect of Displacement Between Opposing Waveguides

Referencing the state when the flange surfaces of two waveguides with propagation axes on the same straight line are directly opposed with a gap of $g = 0.05$ mm, the

displacement (offset) from this position is expressed as $(\Delta x, \Delta y)$ [mm]. Here, Δx and Δy follow the coordinate system shown in Figures 1(a) and (b). The waveguide propagation axes are kept parallel, and angular misalignment is not considered. A displacement of 0.05 mm was applied in each direction, and $|S_{21}|$ was evaluated by harmonic analysis. Figure 14 shows the harmonic analysis results for simple, non-split, flat elliptical quadruple, and split elliptical chokes with intentional displacement in the x and y directions. Table 1 summarizes the resonance frequencies determined from the analysis results in Figure 14. A peak is observed (Figure 12 (solid pink line)) at 255 GHz from the measurement results of the flat elliptical quadruple choke. Since this frequency matches the peak that occurs when a displacement of $\Delta x = 0.05$ mm is applied, this is believed to be due to offset in the x direction.

Despite the harmonic analysis results for the split elliptical choke not exhibiting (Figure 14(c)) clear resonances, the measured results (Figure 13(a) (solid green line)) for the split elliptical choke have four peaks at locations indicated by red arrows. To verify this difference, a harmonic analysis was performed by incorporating the actual flange shape shown in Figure 15(a) into the model. Figure 15(b) shows the result. Figure 15(b) replots the actual measured results from Figure 13(a) (green solid line) for comparison. As shown by the green dotted line, there are peaks at the four places indicated by the red arrows, and these match the actual measured results (green solid line). Therefore, the resonance observed in the split choke is not due to misalignment between the waveguides, but is thought to be caused by reflections at the WR-3 flange end due to the ridge waveguide.

Based on the above, although peaks appear when there is intentional displacement in the x- or y-direction in any of the simple, non-split, and flat chokes, no clear peaks appear in the split choke with any displacement, confirming that the split elliptical choke is less susceptible to misalignment than other elliptical chokes.

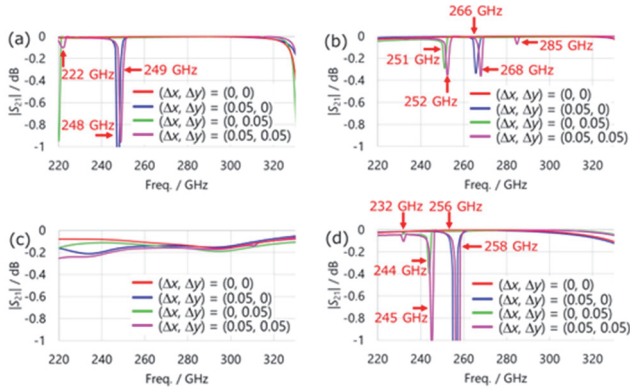


Figure 14 Harmonic analysis results when Δx , Δy displacements of (0.05, 0), (0, 0.05), (0.05, 0.05) mm applied to opposing standard waveguide ($g = 0.05$ mm) (a) Simple elliptical quadruple choke, (b) Non-split elliptical quadruple choke, (c) Split elliptical choke, (d) Flat elliptical quadruple choke

Table 1 Resonance frequencies when Δx , Δy displacements of (0.05, 0), (0, 0.05), (0.05, 0.05) mm applied to opposing standard waveguide ($g = 0.05$ mm) (a) Simple elliptical quadruple choke, (b) Non-split elliptical quadruple choke, (c) Split elliptical choke, (d) Flat elliptical quadruple choke

		unit / GHz	
Δx / mm	Δy / mm	0	0.05
0	0	248	
0.05	0	—	222, 249

		unit / GHz	
Δx / mm	Δy / mm	0	0.05
0	0	266	
0.05	0	251	252, 268, 285

		unit / GHz	
Δx / mm	Δy / mm	0	0.05
0	0	—	—
0.05	0	—	—

		unit / GHz	
Δx / mm	Δy / mm	0	0.05
0	0	256	
0.05	0	244	232, 245, 258

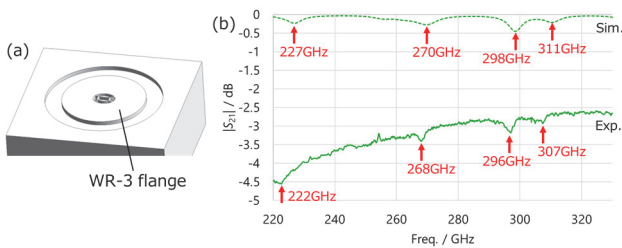


Figure 15 Results of actual measurements of split elliptical choke and harmonic analysis results considering WR-3 flange (a) Shape of analysis model, (b) $|S_{21}|$ measured and harmonic analysis results

7 Conclusions

Chokes are designed originally to perform in narrow bandwidths, and broadening their bandwidth is technically difficult. This article considers four elliptical choke designs (simple, flat, split, and non-split) that operate across the full WR-3 band, and demonstrates their effectiveness through

simulations and actual measurements. Additionally, harmonic analysis comparing changes in transmission loss due to waveguide misalignment confirmed that the split elliptical choke is less susceptible to the effects of waveguide misalignment. However, the split elliptical choke has a larger leakage loss of ≤ 14 dB compared to the other three types of chokes and finding a more effective solution is a task for the future.

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Authors



Yusa Takemoto
2nd Laboratory
Advanced Research Laboratory



Shigenori Mattori
2nd Laboratory
Advanced Research Laboratory

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