Tunable Filter Technology for mmWave THz-band Spectrum Analyzer

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[Summary] The future expected increase in mobile traffic volumes will require use of the mmWave and THz bands, which are wide frequency bands that are not currently in use. Consequently, currently there is no spectrum analyzer for development of wireless equipment supporting these frequencies. One reason is the difficulty in developing a tunable preselector filter. This article introduces an FPW filter (70 to 140 GHz) as well as a waveguide switch with integrated filter bank (140 to 315 GHz) as possible solutions to this problem, along with some test evaluation results for both these filter designs.

1 Introduction

Future mobile traffic is expected to grow rapidly. As a result, there is a need to use wireless communications in the millimeter wave (mmWave) and THz bands to implement faster transmission speeds of 30 or 40 Gbps[1]. Development of wireless systems requires the spectrum analyzer as a fundamental measuring instrument. Consequently, there is demand for development of a mmWave THz-band spectrum analyzer.

One method for implementing a high-frequency band spectrum analyzer is to combine a general-purpose commercial analyzer with a down-converter using a mixer[2]. Using this configuration causes issues with observing signals that do not actually exist due to the relationship between the signal input to the mixer and the local signal. As a result, it is necessary to suppress the effect of the unwanted signals to measure the wanted signal accurately. One method to achieve this is to insert a tunable filter upstream of the mixer to block signals other than the signals to be observed as shown in Figure 1. This tunable filter is called a preselector.

There are two main methods for implementing a preselector: 1. Changing a resonator frequency to create a tunable filter with a continuously variable passband; and 2. Splitting the used band into several bands and switching a fixed frequency filter for each band using a filter bank. Although the YIG Tunable Filter (YTF)[3] constructed using YIG elements is commonly used as a tunable filter, implementation is difficult at high frequency bands exceeding 70 GHz. On the other hand, filter-bank configurations depend on separate parts, such as a waveguide switch for frequencies above 100 GHz. When configuring a filter bank using

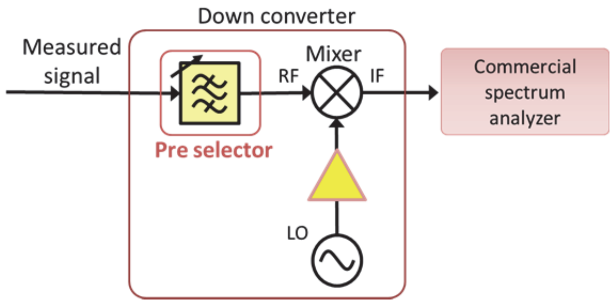

Figure 1 Spectrum Analyzer Block Diagram

these parts, there are problems with the large overall size of the device due to the large parts count. Moreover, there is a tendency for the insertion loss to increase with larger parts counts. As a result, configuring a filter bank by combining many separate parts is unsuitable for a preselector.

To solve these types of problems we have proposed several filter designs for use as a preselector at the frequency bands exceeding 70 GHz. With one method using a Fabry-Perot resonator inside Waveguide (FPW)[4) to 9)], the length of the resonator is changed using a directly connected actuator to change the center frequency of the pass band linearly. This type of filter is small and can be used over a wide frequency band, but the reproducibility of the filter frequency characteristics depends on the actuator positioning reproducibility. Consequently, when the frequency is high and the wavelength is short, the reproducibility of the filter frequency characteristics drops. Moreover, due to the relatively complex structure, the filter performance is heavily affected by machining tolerances. Based on these considerations, the upper frequency limit for these filters is about 140 GHz.

Waveguide switches with an integrated filter bank have been proposed as preselectors for use in the frequency bands above 140 GHz[10) to 13)]. This filter bank is configured with

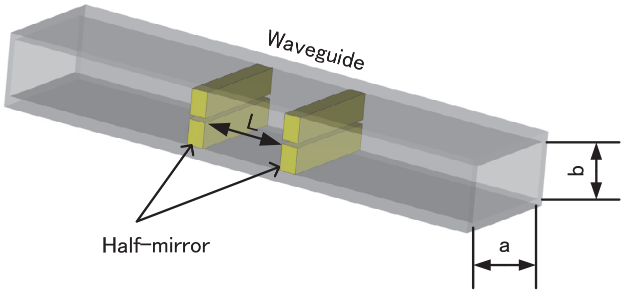

Figure 2 FPW Filter Principle

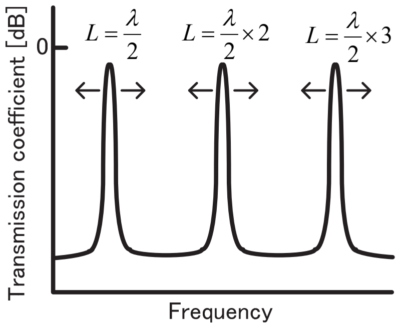

Figure 3 Fabry–Perot Resonator Transmission Characteristics

multiple BandPass Filters (BPF) built into a 1:1 waveguide switch. In comparison to conventional filter banks configured from separate parts, it is both relatively smaller and has a lower insertion loss. Moreover, due to the simple structure it can be implemented for frequency bands above 140 GHz. This article presents some test results for use of this filter bank in the 300-GHz band. Although we tested in the 300-GHz band, we believe it is possible to implement this design for higher frequency bands. However, the design is larger than designs using FPW filters. Moreover, use of fixed-frequency BPFs requires data on how the measured signal frequency band should be divided. Consequently, the BPFs must be designed after designing the entire spectrum analyzer.

This article explains the operating principles and prototype evaluation results for an FPW filter tested in the 70 to 140-GHz band as well as a waveguide switch with integrated filter bank tested in the 140 to 315-GHz band.

2 Tunable Filter (FPW Filter)

2.1 Operating Principle

The FPW filter incorporates a Fabry–Perot resonator used in various optics fields into a waveguide as shown in Figure 2. The Fabry–Perot resonator[14] is composed of two opposite facing half-mirrors. The transmission coefficient of

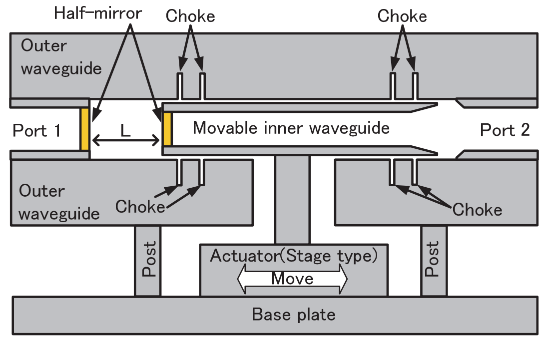

Figure 4 FPW Filter Cross Section E

this resonator becomes maximum when the linear length L between the half-mirror faces (resonator length) is it an integer multiple of the half wavelength as shown in Figure 3. Consequently, the passband center frequency can be swept by changing the linear length between the mirrors.

2.2 Prototype Structure

Figure 4 shows the structure for changing the length L by moving the half-mirrors using an actuator. Figure 4 shows a cross section (E) through the longitudinal center (a/2) of the waveguide aperture. The half-mirror at the Port-1 side of the waveguide is fixed in position, while the second half-mirror is attached to the movable inner waveguide inserted inside the outer waveguide. Moving the actuator at the lower part of the filter moves the movable waveguide inside the outer waveguide, causing a change in the length L of the resonator formed by the separation between the two half-mirrors. The gap between the movable waveguide and the outer waveguide is on the order of 30 µm. This gap helps prevent frictional wear between the movable waveguide and the outer waveguide and increases the filter durability. Moreover, to prevent electromagnetic waves leaking from this gap, the design incorporates channels called a choke with a depth of about one quarter of the guide wavelength. The choke is designed with several channels as necessary. However, although the channels shown in Figure 4 are cut into the side of the outer waveguide, the choke channel design can also be cut into the side of the movable waveguide. In this case the movable waveguide requires sufficient tube wall thickness. The movable waveguide and outer waveguide facing the Port-2 side have a tapered configuration to suppress reflections due to discontinuities in waveguide diameter. Furthermore, as at the Port-1 side, there is also a choke design to prevent electromagnetic wave leakage from the gap between the movable waveguide and the outer waveguide.

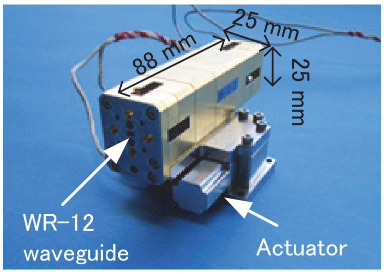

Figure 5 External View of WR-12 Band FPW Filter

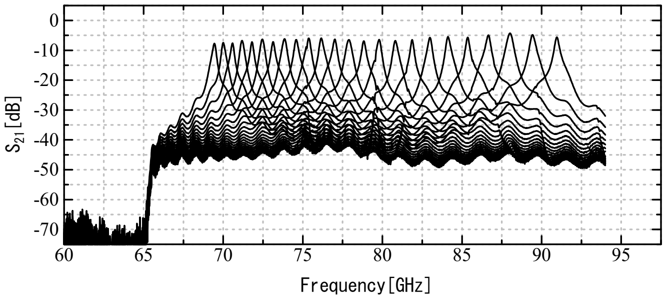

Figure 6 WR-12 Band FPW Filter Measured S_{21} Results (Actuator movable in 50-µm steps)

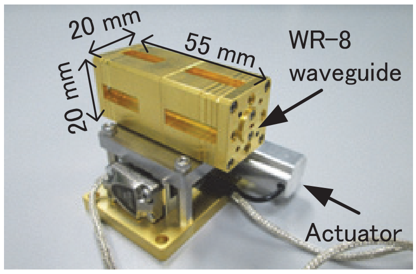

Figure 7 External View of WR-8 Band FPW Filter

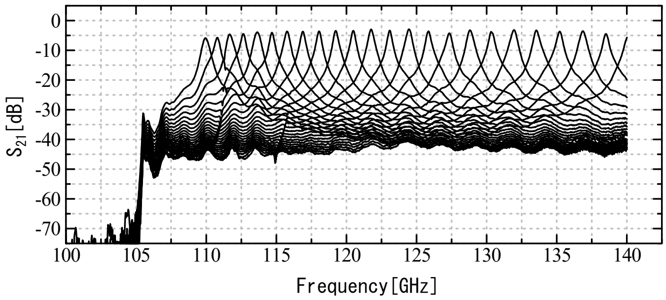

Figure 8 WR-8 Band FPW Filter Measured S_{21} Results (Actuator movable in 20-µm steps)

Designing the half-mirrors with a fixed reflectance coefficient is recommended if possible. If the reflectance coefficient is large, the passband becomes narrow due to the filter's higher Q value. Additionally, the insertion loss also increases. Consequently, it is necessary to select the optimum reflectance coefficient. The half-mirrors in the prototype design were fabricated from metal plates with a slit cut in the H-plane (parallel to longitudinal axis of waveguide aperture). Additionally, since it is difficult to evaluate the reflectance coefficient value close to total reflectivity, evaluation of the half-mirrors was performed using the transmission coefficient. In concrete terms, simulation was performed with only one half-mirror in the waveguide and no loss. Based on these results, the slit width in the half-mirrors was adjusted so that S_{21} was about −20 dB.

2.3 Tested FPW Filter and Evaluation Results

This section presents test results for two types of FPW filter: 1 A WR-12 band FPW filter using the 70 to 90-GHz band; and 2. A WR-8 band FPW filter using the 110 to 140-GHz band. The same actuator was used by both filters for both frequency bands. The actuator reproducibility was ±0.2 µm. The size of this reproducibility caused frequency drift of about ±30 MHz with the WR-8 band FPW filter. However, since the 3-dB passband frequency was better than 300 MHz with this prototype, we believe there were no major usage issues.

2.3.1 WR-12 Band FPW Filter

Figure 5 shows the external appearance of the WR-12 band FPW filter. The dimensions of the main part including the actuator and mounting base are 25 × 25 × 88 mm. It was fabricated from gold-plated Steel Special Use Stainless (SUS).

The actuator position was changed in 50-µm steps and the S_{21} parameter was measured using a Vector Network Analyzer (VNA). Figure 6 shows the superimposed measured S_{21} results, confirming the change in the passband center frequency at 70 to 90 GHz.

The 3-dB passband was on the order of 240 to 400 MHz, depending on the frequency. Moreover, since the half-mirror transmission coefficient was designed to be a constant value within the used band, the pass bandwidth band ratio was also constant. If there is little change in the passband width, it would be better to use a design with a lower transmission coefficient based on the increase in the half-mirror frequency.

The maximum insertion loss was 8.2 dB, which meets the 10 dB max insertion loss required generally for preselectors.

2.3.2 WR-8 Band FPW Filter

Figure 7 shows the external view of the WR-8 band FPW filter. Figure 8 shows the S_{21} result measured in the same way as shown in Figure 6. However, in the Figure 8 measurements, the actuator position was changed 20-µm steps. The dimensions of the main part including the filter actuator are 20 × 20 × 55 mm.

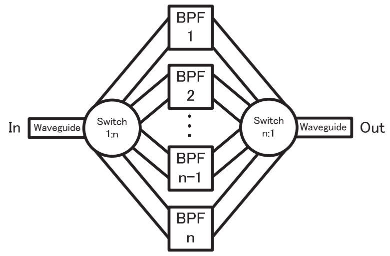

Figure 9 Filter Bank Operation Principle

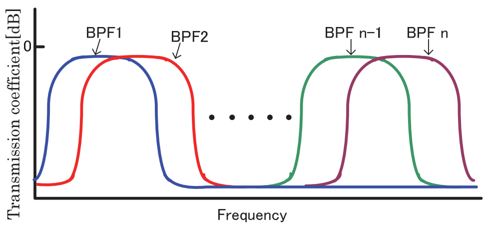

Figure 10 Filter Bank Frequency Characteristics

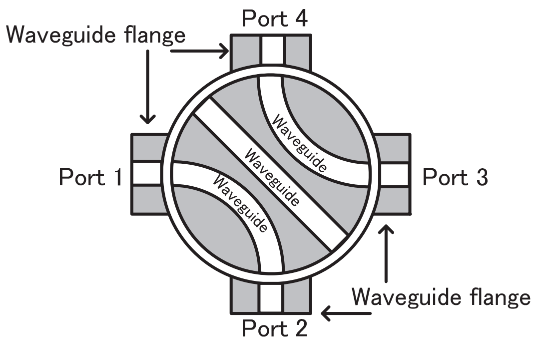

Figure 11 Commercial Waveguide Switch

From Figure 8 we can see that the passband center frequency could be changed at 110 to 140 GHz. The 3-dB passband was 350 to 600 MHz and the insertion loss was 5.8 dB, meeting the 10 dB max value in the same manner as the WR-12 band FPW filter. Based on these results, we confirm that the prototypes had adequate performance for use as preselectors.

2.4 FPW Filter Summary

Based on the test evaluation results, the FPW filter is clearly effective for frequencies up to 140 GHz. The band used in this test is about 25% of relative bandwidth. In addition, wider bandwidths were also targeted[7]. The FPW filter is fabricated from a resonator and multiple parts as well as movable parts. Consequently, assembly presents a high degree of difficulty. For this reason, we believe FPW filters will be difficult to manufacture stably for frequencies above 140 GHz.

3 Filter Bank

3.1 Filter Bank Principles and Issues

Figure 9 shows the operation principle for a mmWave filter bank. The filter bank switches the passband as shown in Figure 10 using multiple BPFs and waveguide switches.

Figure 11 shows the well-known commercial 1:3 waveguide switch[15] which performs switching by rotating the center part. However, this design causes problems when supporting more than 1:3 switchings.

When using a filter bank as a preselector, dividing the used bandwidth into many bands requires switching to a BPF designed for each band. As a result, using the 1:3 switch in such a design would require many switches. In addition, fabricating a filter bank by assembling commercial components requires connecting each component via the waveguide which makes the device much larger and is also expected to increase insertion loss. Furthermore, waveguide switches perform switching using physical rotation which results in degraded performance due to wear at the waveguide contact surfaces. To use the filter bank as a preselector for a spectrum analyzer, it is critical to minimize the size of components inside the instrument as well as to reduce insertion loss. Moreover, the filter bank must have very high durability to withstand presumed continuous operation.

3.2 Operation Principle of Waveguide Switch with Integrated Filter Bank

To solve the previously described issues, we propose fabricating a waveguide switch with integrated filter bank. The filter bank is incorporated as several BPFs in a one-to-one waveguide switch.

Figure 12 shows cross-section H of the proposed filter bank, which is fabricated from three parts: a fixed part at the input side, a movable part, and fixed part at the output side. The several BPFs are mounted in parallel on the movable part. The filter bank switches the connected BPF by moving the movable part using an actuator.

In addition, the fixed part at the input side and the movable part, and the fixed part at the output side and movable part are separated by narrow non-contact air-gap to prevent degraded performance resulting from frictional wear. Since increased insertion loss due to leakage of electromagnetic waves from these gaps is assumed, a choke was designed to border the waveguide aperture. The red oval in

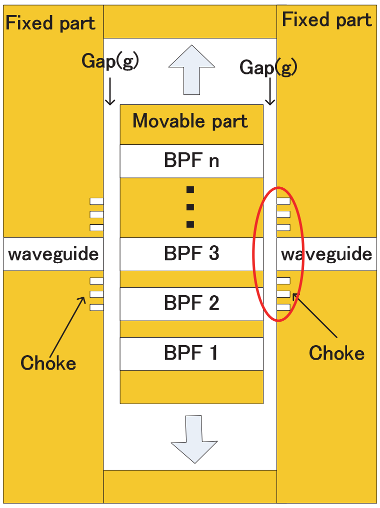

Figure 12 Proposed Filter Bank Cross-Section H

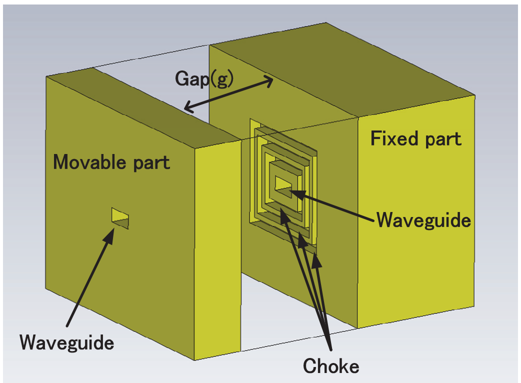

Figure 13 Magnified View of Waveguide Surfaces

Figure 12 shows the location of the choke magnified in Figure 13 where the choke is clearly seen surrounding the waveguide. Leakage of electromagnetic waves to the outside can be prevented by locating this choke appropriately. As a result, the connecting surface between the fixed and movable parts of the waveguide supports both high isolation and low insertion loss. In Figure 13, the waveguide aperture is surrounded by three choke channels, but this number can be increased or decreased as necessary, according to the required characteristics.

Based on the above-described structure, we expected to be able to fabricate a small filter bank with low insertion loss because there is no necessity to connect individual components and nor is there a necessity to use multiple waveguide switches. Additionally, the non-contact surfaces between fixed and movable waveguide parts suppress degraded performance due to wear.

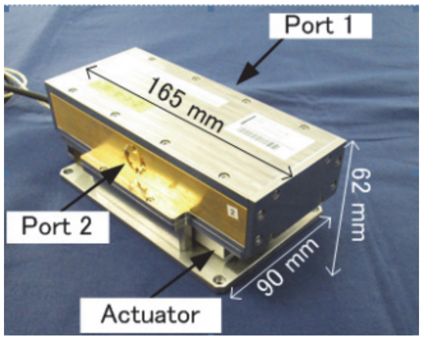

Figure 14 External View of WR-5 Band Filter Bank

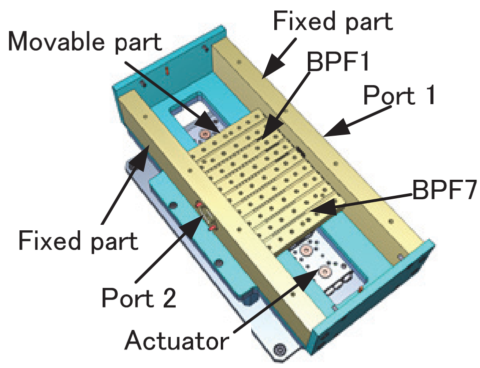

Figure 15 WR-5 Band Filter Bank Internal Structure (without cover and top half of movable part)

3.3 Tested Filter Bank and Evaluation Results

3.3.1 Prototype Structure

We tested three waveguide switches with integrated filter bank for the WR-5 (140 to 190 GHz), WR-4 (185 to 260 GHz), and WR-3 (255 to 315 GHz) bands. The tested parts were of different dimensions due to the different size of the movable part resulting from the number of BPFs corresponding to band divisions. Other parts were common to each switch.

As examples of the tested filter banks, Figure 14 shows the external view of the WR-5 band filter bank with a size of 165 × 70 × 62 mm. However, the WR-4 and WR-3 filter banks were both 172 × 70 × 62 mm. Although these filter banks are larger than FPW filters, they are still small enough to be installed in a measuring instrument.

Figure 15 shows the internal structure of the WR-5 band filter bank with the cover and top half of the movable part removed. As shown in Figure 12, it is fabricated with the movable part between two fixed parts. The movable part is moved by an actuator underneath it, which results in switching of the connected BPF. The movable part incorporates seven bandpass filters BPF1 to BPF7 as well as a section with no filter.

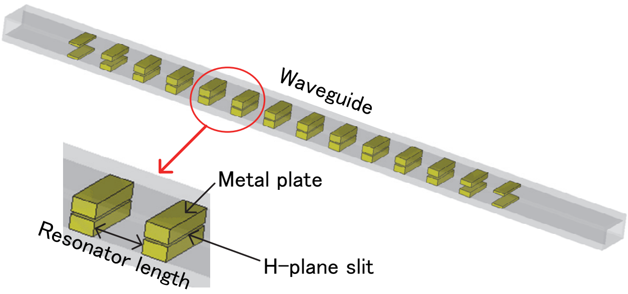

Figure 16 Structure of WR-5 Band Filter Bank BPF7

Each BPF is fabricated within the waveguide as parallel-aligned metal plates with a slit in the H-plane. Figure 16 shows an image for BPF7 in the WR-5 filter bank with metal plates aligned in parallel with the H-plane slit indicated in yellow. The gap between these metal plates is the resonator. The BPF pass frequency is determined by the length of this resonator. In addition, the degree of coupling between resonators can be changed by adjusting the slit width. The BPF transmission characteristics are determined by these factors. Consequently, the number of metal plates and each parameter specification was optimized by simulating the electromagnetic fields.

3.3.2 WR-5 Band Filter Bank Evaluation Results

The WR-5 band filter bank was designed to split the 140 to 190-GHz bandwith (relative bandwidth 30%) into seven bands. The specification for each BPF was determined according to the design of the spectrum analyzer using the filter bank.

The BPFs were switched by moving the actuator and S_{21} of the tested filter bank was measured using a VNA. Figure 17 shows the superimposed measured S_{21} results, clarifying that the seven bands can be switched as designed. In addition, a stopband of better than 70 dB was confirmed. Based on these results, we believe that the wraparound choke design adequately suppressed leakage of electromagnetic waves from the gap between the movable and fixed parts of the waveguide. Moreover, the passband maximum insertion loss was 4.3 dB.

3.3.3 WR-4 Band Filter Bank Evaluation Results

The WR-4 band filter bank has a maximum relative bandwidth in the tested filter banks. The tested filter bank was designed to split the 185 to 260-GHz bandwidth (relative bandwidth 34%) into nine bands, and Figure 18 shows the measured S_{21} results, confirming the filter bank operation even when the usage range was extended beyond the WR-5 filter bank. Moreover, the maximum insertion loss in the usage band was 4.0 dB.

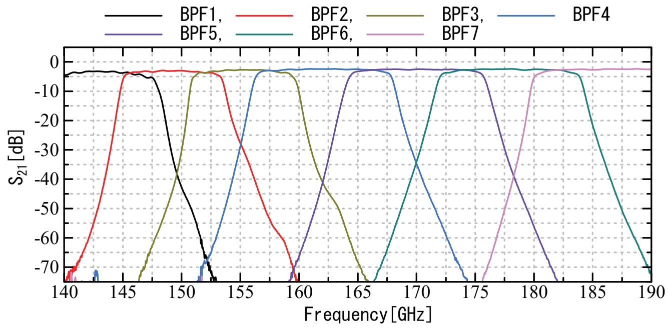

Figure 17 WR-5 Band Filter Bank Measured S_{21} Results

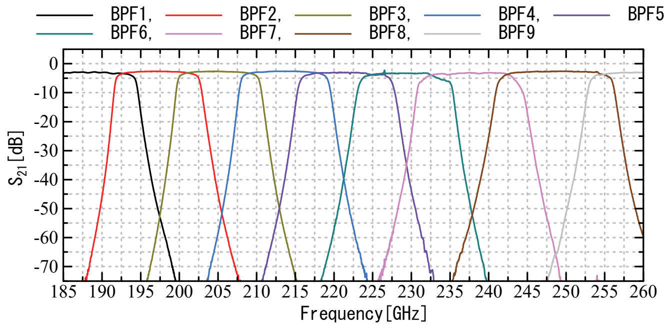

Figure 18 WR-4 Band Filter Bank Measured S_{21} Results

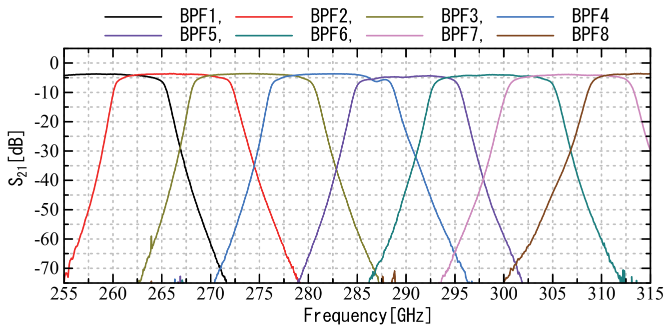

Figure 19 WR-3 Band Filter Bank Measured S_{21} Results

3.3.4 WR-3 Band Filter Bank Evaluation Results

The WR-5 band filter bank was designed to split the 255 to 315-GHz bandwidth (relative bandwidth 21%) into 8 bands, and Figure 19 shows the measured S_{21} results, confirming the filter bank operation even at high frequencies, such as 300 GHz. The insertion loss of 5.6 dB was higher than filter banks for other bands due to the higher frequency.

3.4 Waveguide Switch with Integrated Filter Bank Summary

Tested filter banks for each band achieved large isolation as well as a maximum insertion loss of 10 dB. Based on these results, we have confirmed that the developed filter banks have adequate performance for use as preselectors in a spectrum analyzer. Additionally, unlike FPW filters, these filter banks are fabricated using fixed BPF parts. As a result, these filter banks suffer less degraded performance due to the impact of assembly. Moreover, the required actuator reproducibility is low; reproduceability of only about 5 µm is sufficient even for the 300-GHz band. Based on these points, we believe we can fabricate filter banks even for frequencies above 300 GHz.

4 Conclusion

This article has introduced tunable FPW filters used as preselectors for the 70 to 315-GHz frequency band as well as a new method for implementing preselectors using a waveguide switch with integrated filter bank. Both methods implement mechanical operation using an actuator, which can suffer from wear-related degraded performance. However, the introduced filter bank achieves high durability and low insertion loss by using technologies such as non-contact surfaces between moving and fixed parts to minimize degraded electrical characteristics. Prototypes were tested at operation ranges up to 315 GHz, but we believe operation frequencies above this range can be supported using the waveguide switch with integrated filter bank. This will be confirmed by future test results.

Use of the introduced preselectors will help development of high-accuracy spectrum analyzers supporting frequency bands that have been difficult to measure until now. We hope this research and development will play a key role in development of mmWave THz-band wireless systems.

Acknowledgments

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