Tunable Filter for Millimeter Waveband Spectrum Analyzer over 100 GHz

Takashi Kawamura, Hiroshi Shimotahira, Akihito Otani

[Summary] Rapid progress in millimeter-wave wireless communication technologies requires accurate spectrum analysis in the frequency domain over 100 GHz. A tunable preselection filter is a key device in building such a spectrum analyzer. This paper proposes a new tunable filter as a preselector in the frequency range from 110 to 140 GHz. The filter was designed using a commercial electromagnetic simulator and a prototype was evaluated. The prototype measurement results support use of this filter for a preselector.

1 Introduction

Research into applications [1], [2] using the millimeter waveband, such as Wireless Personal Area Networks (WPAN), has been making good progress in recent years. Development of stable wireless systems using the millimeter waveband requires evaluation of secondary harmonic waves in the 60 to 70-GHz band, as well as in the waveband above 100 GHz. However, this evaluation technology is not yet established because there is still no spectrum analyzer supporting both high-sensitivity and high-accuracy in the millimeter waveband. Consequently, development of a high-accuracy spectrum analyzer supporting the millimeter waveband is eagerly anticipated.

Developing a high-accuracy spectrum analyzer requires a preselector for suppressing the image response. Conventional millimeter waveband preselectors use a Yttrium Iron Garnet (YIG) tuned filter (YTF)[3]. However, currently there is no commercial YTF supporting frequency bands over 100 GHz. Moreover, use of a YTF also requires an extremely powerful magnetic field, consuming large amounts of power to create. Not only does YIG have a high temperature coefficient but it also has clear aging characteristics causing an unstable center frequency for filter applications. Additionally, it has a problem of large insertion loss in the millimeter waveband.

As a result, we propose development of a new millimeter waveband tunable filter for use as a preselector in the bandwidth from 110 to 140 GHz. This filter functions by performing mechanical tuning [6], [7] of a Fabry-Perot resonator [4], [5] mounted in a waveguide. This article first outlines a high-accuracy, millimeter waveband spectrum analyzer currently under investigation and then describes the operation principles of a millimeter waveband filter. It shows some design results using an electromagnetic simulator and concludes with the evaluation results for a prototype filter.

2 Outline of Millimeter Waveband Spectrum Analyzer

Figure 1 shows the block diagram for a millimeter waveband spectrum analyzer currently under investigation. To measure wireless signals between 110 and 140 GHz with both high dynamic range and high sensitivity, this spectrum analyzer is composed of a fundamental wave mixing type frequency converter (low conversion loss, small front head, and local signal generator) plus an existing general spectrum analyzer. The millimeter waveband tunable filter proposed in this article is used as the preselector for the low-conversion-loss, small-front-head section.

Moreover, although this idea of combining the existing technologies of a frequency converter using a harmonic mixing method and an existing general spectrum analyzer makes it possible to measure RF signals above 110 GHz, with this method, the frequency conversion rate is extremely low, the very small spurious is buried under noise, and the dynamic range is narrow. As a consequence, when the measured RF signal spreads across a wide bandwidth, a diffused signal image is created, making accurate signal measurement difficult.

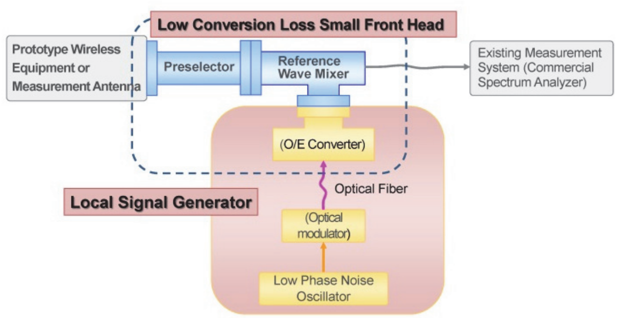

Figure 1 Block Diagram of Millimeter Waveband Spectrum Analyzer

3 Millimeter Waveband Filter Operation Principle

The Fabry-Perot resonator is composed of two opposite-facing half-mirrors. As shown in Figure 2, when the length of the path L (resonator length) between the two half-mirror surfaces is the half-integer multiple of the wavelength, the transmission coefficient becomes maximum. As a result, the passband center frequency can be swept by changing the length of the path between the half-mirrors.

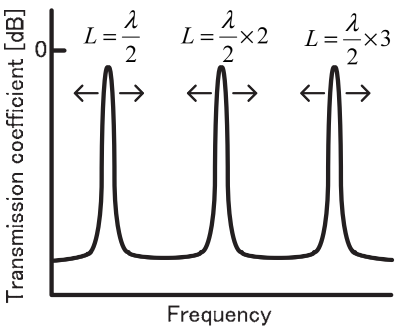

Figure 2 Transmission Characteristics of Fabry-Perot Resonator

Half-mirrors used in Fabry-Perot resonators can be spherical or planar and a combination of each type can be used to configure a confocal, concentric, or parallel-plate type resonator. The confocal type shown in Figure 3 is frequently used due to its easy adjustment but the distance between the mirror faces increases and decreases at passband sweeping, causing focal point drift as well as problems with finesse or lowered resonator Q value. As a consequence, the confocal type is not suitable for tunable filters, and the parallel-plate type shown is Figure 4 is used instead. Even so, achieving a tunable filter using this type faces the following two problems.

- The planar wave must be inserted parallel to the half-mirror. If this condition is not met (planar wave angled insertion or spherical wave), the phase is not aligned at the inserted wave mirror face and the finesse drops.
- The loss is large due to radiation into free space as a result of the open design.

Using a waveguide input to the filter as the planar wave insertion method and increasing the waveguide diameter like a horn antenna can create a planar wave, but it is difficult to achieve a completely planar wave due to the incurred increase in the occupied area.

To solve these problems, we proposed fabricating the filter shown in Figure 5 by designing a Fabry-Perot resonator inside a waveguide. Two half-mirrors are arranged in the square waveguide to transmit only the fundamental mode (TE_{10} mode). The distance L between the two half-mirrors is found as $L = \lambda_g/2$ when the guide wavelength λ_g corresponds to the center frequency f_c for the required passband. The length of the transmitted wave path must be determined uniquely to transmit only the TE_{10} mode in the waveguide with this type of structure. If the path distance can be changed sufficiently, it is possible to achieve a wideband tunable filter. In addition, loss of radiation to free space is eliminated entirely by using a closed design. Moreover, deformation due to temperature changes in the metallic waveguide become smaller with wavelength, offering the advantage of reduced effects of temperature change compared to the YTF.

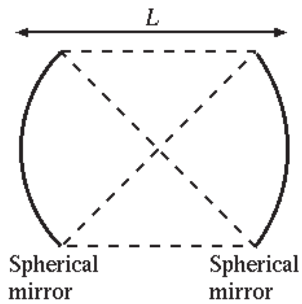

Figure 3 Confocal Fabry-Perot Resonator

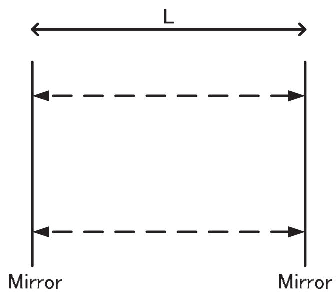

Figure 4 Parallel-plate Fabry-Perot Resonator

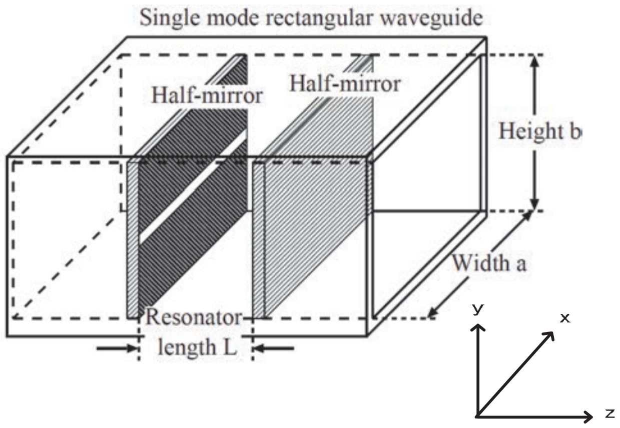

Figure 5 Proposed Filter Schematic

The operation principles of the proposed filter were verified using simulations based on the schematic in Figure 5. The main simulation conditions are summarized in Table 1. However, for simplicity, the losses of the waveguide and half-mirrors were ignored. The half-mirrors which are described in next section used a metallic slit on dielectric substrate (Figures 7 and 12). L was determined as half the guide wavelength for the TE_{10} mode at f_c = 125 GHz. The value of Q was found from Eq. 1

$$Q = \left(1 + \left(\frac{L}{a}\right)^2\right) F \text{ , } F = \frac{\pi\sqrt{R}}{1-R}, \qquad (1)$$

Where, F is the finesse of the Fabry-Perot resonator in free space, and R is the reflection coefficient of the half-mirror. Figure 6 shows the simulation results. In comparison with the design values (Table 1), the simulation center frequency was 127.1 GHz compared to 125 GHz for the design value (within 2%). Additionally, the simulation value of Q calculated from the full-width half-maximum (FWHM) of the filter transmission band was 514 compared to the design value of 503 (similarly within 2%). These results validated the design and confirm that this filter operates as a Fabry-Perot resonator.

Table 1 Simulation Conditions

Center Frequency	f_c=125 GHz
Waveguide Dimenions	WR-08 a = 2.032 mm, b = 1.016 mm
Half-mirror Reflection Coefficient	R = 0.9905 @ 125 GHz
Oscillator Length	L = 1.478 mm
Q (calculated from (1))	503

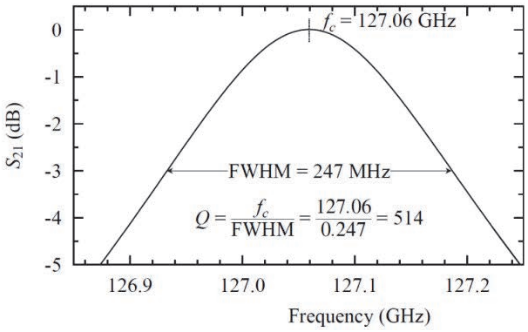

Figure 6 Simulated S_{21} Frequency Characteristics

All simulations were performed using CST MI-CROSTRIPES™ based on the Transmission Line Matrix (TLM) method.

4 Prototype Design

Ideally, the tunable filter should have a fixed value of Q in the freqency tuning range. From Eq. (1), since the value of Q is determined by the reflection coefficient of the half-mirror, the prototype was designed so that R is a fixed value. On the assumption that the frequency tuning range width is 110 to 140 GHz with a center frequency f_c of 120 GHz and an FWHM of 300 MHz, the reflection coefficent R must be 0.99 (–0.04 dB) to give a Q value of about 400. Since it is difficult to accurately simulate the reflection coefficient near 0 dB, the characteristics were evaluated using the transmission coefficient targeting –20 dB for the value at 110 to 140 GHz. To achieve these characteristics, we used a half-mirror combining a capacitive window on a metallic plate and a dielectric substrate with slopes of opposite sign for S_{21}. Silicon was used as the dielectric and the capactive window design was simulated as an Au vapor-deposited slit in a silicon substrate to obtain the ideal half-mirror shown in Figure 7. Figure 8 shows the frequency characteristics of the half-mirror. From Figure 8, the value of S_{21} falls between –20.16 and –20.26 dB at 110 to 140 GHz. The half-mirror was fabricated based on the structure in Figure 7.

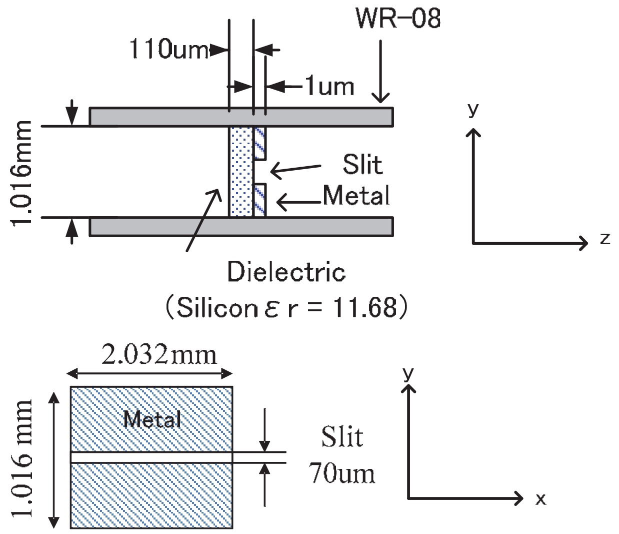

Figure 7 Half-mirror Structure

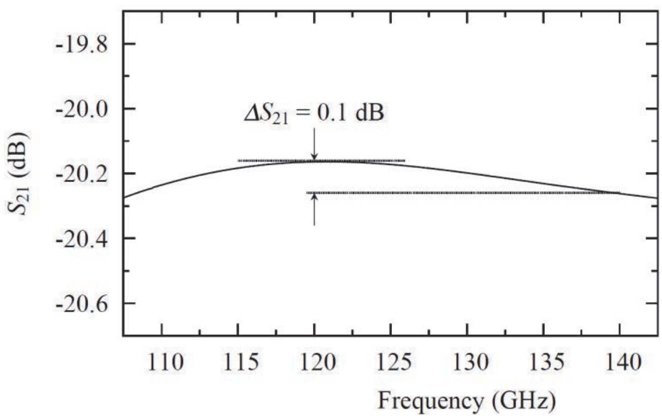

Figure 8 Frequency Characteristics of Ideal Half-mirror

The millimeter waveband filter was simulated using this half-mirror. Figure 9 shows a cross-section of the prototype, and Table 2 summarizes the main specifications of the prototype and the simulation conditions. To change the value of L, the inner waveguide mount for the half-mirror was inserted into an outer waveguide allowing the inner waveguide to move. Since there is a slight narrow clearance between the inner and outer waveguides to allow the movement, the design incorporates a choke structure preventing leakage of the transmitted wave. Figure 10 shows the simulation results for the prototype design. Although Figure 10 shows increased insertion loss near 140 GHz, the simulation verified operation as a tunable filter from 110 to 140 GHz. The actual prototype millimeter waveband tunable filter was fabricated based on the above design simulations.

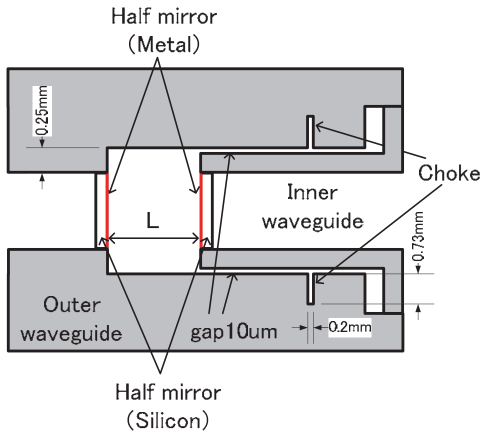

Figure 9 E-plane Cross Section of Prototype

Table 2 Prototype Specifications and Simulation Conditions

Tuning Frequency	110 GHz to 140 GHz (30-GHz bandwidth)
Internal Waveguide Standard	EIL Standard WR-08
Waveguide Total Length	5.0 mm + Oscillator Length L
Half-mirror	See Figure 3.
Materials	External waveguide: Brass ($\sigma = 2.74 \times 10^7$ S/m) Internal waveguide: SUS ($\sigma = 1.60 \times 10^6$ S/m) Half-mirror: Au ($\sigma = 4.5 \times 10^7$ S/m) Silicon ($\varepsilon r = 11.68$, $\tan\delta = 0.002$)
Oscillator Length L	1.65 mm, 1.45 mm, 1.20 mm

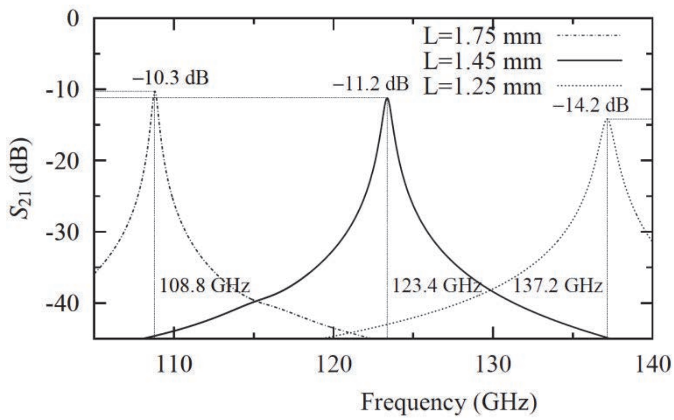

Figure 10 Simulated S_{21} Frequency Characteristics

5 Millimeter Waveband Tunable Filter Prototype

Figure 11 shows the external appearance of the fabricated millimeter waveband tunable filter and Figure 12 shows the half-mirror, which uses a silicon substrate with a metallic slit and is mounted in the inner waveguide. The inner waveguide is operated by an external actuator to change the resonator length L and perform frequency tuning. The interface design mates the prototype to the WR-08 waveguide using a UG-387/UM flange. The total length excluding the actuator is 40 mm × 60 mm.

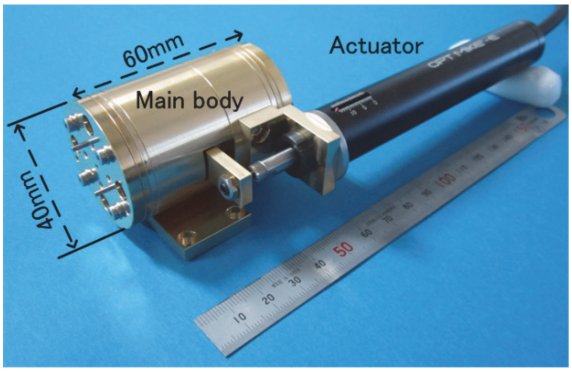

Figure 11 External View of First Prototype

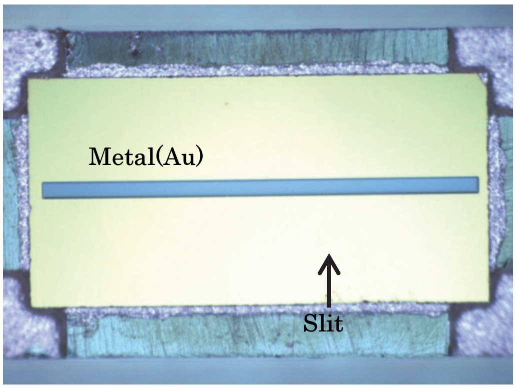

Figure 12 Half-mirror Mounted at Inner Waveguide

6 Prototype Measurement and Evaluation

The prototype millimeter waveband tunable filter was measured using the Anritsu 37169A Vector Network Analyzer and a frequency extender (OML V08VNA2-T/R-A). To evaluate the center frequency f_c characteristics with changes in the resonator length L, the S-parameter frequency characteristics were measured by changing L in 10-µm steps. In this article, the center frequency f_c for the measured results was found from the $(f_R + f_L)/2$, where f_R and f_L are the respective frequencies for the high and low regions when S_{21} is 3 dB below the minimum insertion loss (max. value of S_{21}).

Figure 13 shows the measurement results for two prototype millimeter waveband tunable filters #1 and #2 as well as the theoretical values of the resonance frequency for L. Measured frequency vs L changes monotonously and is in close agreement with the theoretical value in this range. Here, the value of L is calculated by subtracting the actuator displacement amount from the 1.9 mm max. value of the mechanical design. Consequently, it is not the true resonator length, but includes some error due to the assembly construction. We believe the differences between the measured results for filters #1, and #2 and the theoretical values are due to these differences in assembly.

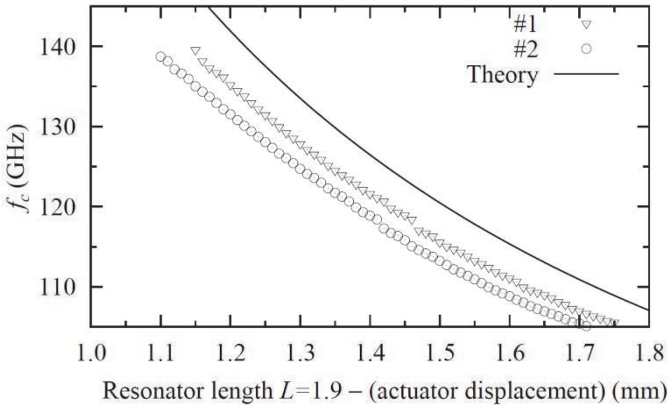

Figure 13 Measurement of f_c as Function of L

Next, we moved the actuator of prototype #1 from the maximum resonator length L of 1.9 mm to the minimum of 1.1 mm in 10-µm steps and measured the center frequency f_c. This procedure was repeated 10 times to verify the resonance frequency repeatability. Figure 14 shows the center frequency f_c evaluation result when the resonator length L of prototype #1 was 1.4 mm, indicating a dispersion of 70 MHz. The repeatability of the actuator used in this test was 2 µm, so in theory, changing L by 1 µm should produce a change in f_c of about 70 MHz near 120 GHz, indicating the measured result dispersion is within the actuator repeatability range.

Finally, to evaluate insertion loss, the results of the first measurement are summarized as insertion loss in Figure 15, showing the frequency and level for the maximum value of S_{21} as the resonator length L changes for both of the two prototypes. In addition, the simulated results as L changes in 50-µm steps have been added as a solid line. Comparisons of the simulations and measurements clarify two features. First, the measured losses are about 5 dB greater than the simulations across the entire bandwidth. Second, the trends in the frequency characteristics are similar for both the simulations and measurements, and loss increases near 116 GHz. The similar trends in the frequency characteristics indicate that the simulations are good models of the prototypes. As a result, we hypothesize that the cause of the increased loss observed in item 1 is due to differences between the electrical constants of the materials (conductivity, etc.) used in the simulations and the fabricated prototypes. Future work requires clarification of this difference by evaluating presumed coefficients used for test parts. With respect to item 2, in designing half-mirrors with flat frequency characteristics, we made assumptions about the effect of structures other than the mirrors. Future simulations should analyze these structures too.

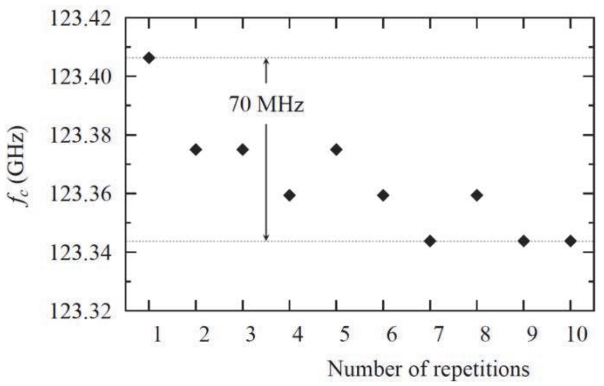

Figure 14 Repeatability Test (f_c at same L = 1.4 mm)

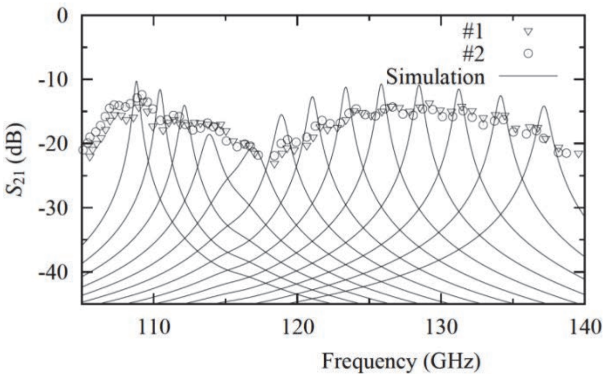

Figure 15 Measured Insertion Losses and Simulated Frequency Characteristics

7 Conclusion

We proposed a millimeter waveband tunable filter constructed using a Fabry-Perot resonator in a waveguide as a preselector for a millimeter waveband spectrum analyzer. First, we verified the operation principles by simulation, demonstrating the design method for fabrication of a half-mirror with flat frequency characteristics, and showing how to achieve sweeping of center frequencies in the 110 to 140 GHz band. Next, we fabricated the prototype filter, evaluated its characteristics, and verified that the design frequency sweeping was achieved. Based on the performance evaluations, we evaluated how to improve the insertion loss beyond the design values by selection of materials and re-examination of manufacturing methods in preparation for development of a second prototype.

Acknowledgments

This work was carried out under the sponsorship of the R&D program for expansion of radio resources promoted by the Ministry of Internal Affairs and Communications, Japan. The authors thank the members of the project advisory committee for their helpful discussions.

References

1) A. Hirata, T. Kosugi, H. Takahashi, R. Yamaguchi, F. Nakajima, T. Furuta, H. Ito, H. Sugahara, Y. Sato, T. Nagatsuma: “120-GHz-Band Millimeter-Wave Photonic Wireless Link for 10-Gb/s Data Transmission”, IEEE Transactions on Microwave Theory and Techniques, Vol. 54, No. 5, pp. 1937–1944, May 2006

2) Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension, IEEE Standard 802.15.3c-2009, 2009

3) J. Helszajn, *YIG Resonators and Filters*, New York, John Wiley & Sons, 1985

4) G. Kuwabara, *Optical Technology,* Kyoritsu, Tokyo 1984 (in Japanese)

5) B. Komiyama, M. Kiyokawa, T. Matsui: “Open Resonator for Precision Dielectric Measurements in the 100 GHz Band”, IEEE Transactions on Microwave Theory and Techniques, Vol. 39, No. 10, pp.1792–1796, Oct 1991

6) T. Kawamura, A. Otani: "Proposal for Millimeter Waveband Tunable Filter", Institute of Electrical Engineers of Japan Measurement Meeting Study Group Document, IM-12-004, pp. 17–21, Jan 2012 (in Japanese)
7) T. Kawamura, A. Otani: "Test Evaluation of Millimeter Waveband Tunable Filter", Institute of Electrical Engineers of Japan Measurement Meeting Study Group Document, IM-12-028, pp. 33–38, Jun 2012 (in Japanese)

Trademarks

Authors

Takashi Kawamura
R&D Control Group
R&D Center
First Development Department

Hiroshi Shimotahira
R&D Control Group
R&D Center
First Development Department

Akihito Otani
R&D Control Group
R&D Center
First Development Department
and Technology Management Center