Multi-band Filter Isolator

Technology Reports

Multi-band Radio Frequency Circuits for Mobile Terminals

New frequency bands are coming to be used in many regions around the world to support implementation of Long Term Evolution (LTE) and other new wireless-communication standards. The conventional method of providing separate radio frequency circuits for each frequency band has the drawback of increasing the size of the radio-frequency-circuit section and driving up costs, and research has consequently been active on developing a single radio frequency circuit that can support a variety of frequency bands. This article focuses on filters and isolators as key devices making up a radio frequency circuit, and proposes configurations that enable the frequency characteristics of these devices to be adaptively varied. The characteristics of each prototype device are presented and future research issues are described.

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1. Introduction

Future wireless communication services will exist in a radio environment consisting of a variety of wireless-communication systems. This suggests the desirability of enabling the most appropriate wireless-communication system to be adaptively selected based on the user's surroundings and requirements, such as the user's current location, time of day, available frequencies, and required transmission speed. From the user's standpoint, this would mean the ability to use the most satisfying wireless-communication system in the case that W-CDMA, LTE and wireless LAN, for example, are all available.

The use of new frequency bands has been studied to secure more bandwidth as data communications increase in capacity. Against this background, mobile terminals of the future should be able to communicate via systems featuring a variety of frequency bands and bandwidths. To that end, the Radio Frequency (RF) circuit[*1] built into the terminal must be able to process signals on different frequency bands.

As shown in **Figure 1** (a), multiple frequency bands in the RF-circuit section of a mobile terminal (multi-band capability) have so far been supported by incorporating as many individual RF circuits as needed for the frequency bands deemed necessary and switching from one circuit to another as required [1]. A drawback of this technique is that the number of RF circuits that must be incorporated increases as the number of frequency bands to be accommodated increases. More RF circuits drive up costs as the number of components increases while also increasing the size of the mobile terminal as the area occu-

*1 **RF circuit**: A radio circuit consisting of a power amplifier, filter, or other device for handling RF signals, or these devices as a whole.

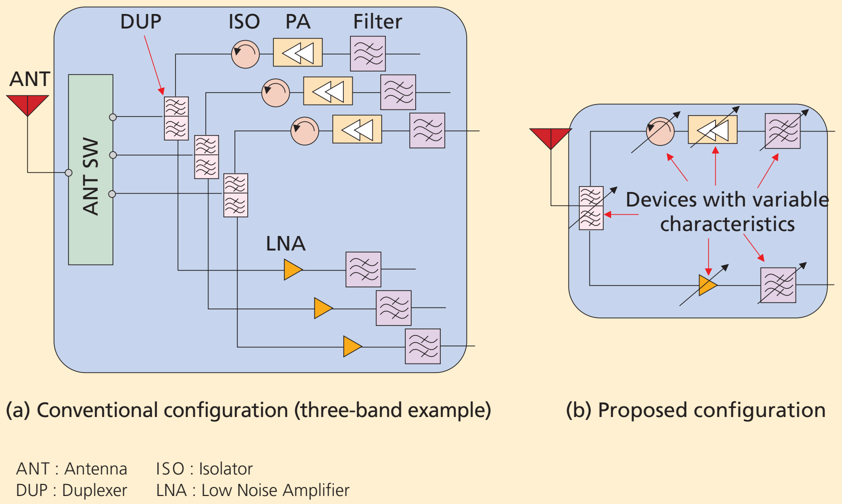

Figure 1 Multi-band RF circuit configurations

pied by the RF circuits expands.

In response to this issue, we have proposed a multi-band technique based on a RF circuit whose frequency characteristics can be varied as shown in Fig. 1 (b). In addition to providing a single multi-band RF circuit, this technology helps to minimize the area occupied by the RF-circuit section in the terminal [2]. Among the devices that make up the RF circuit shown in Fig. 1(b), we have treated the three devices listed below as key devices and undertaken to make their frequency characteristics variable.

- Power Amplifier (PA)
- Filter (as well as transmit/receive duplexer)
- Isolator

We have already reported on a PA that can support nine frequency bands by using a Switch (SW) to vary frequency characteristics [3].

In this article, we describe a newly devised circuit configuration that can vary the frequency characteristics of filter and isolator devices. We also present the results of measuring the frequency characteristics of our prototype devices and touch upon future research issues.

2. Achieving Variable Filter Characteristics

Given, for example, signals of various frequencies received through an antenna, a filter has the function of extracting signals of targeted frequencies while removing signals of unwanted frequencies. In this article, we focus in particular on the Bandpass Filter (BPF)[*2]. Two main parameters can be considered for a BPF: the center frequency (f_c), which is the frequency at the center of the frequency band to be extracted (pass band), and Bandwidth (BW), which is the width of the pass band.

In previously reported BPFs (as in [4]) whose frequency characteristics can be varied (tunable BPFs), both f_c and BW can be varied, but changing BW will unintentionally change f_c as well. In short, it is difficult to vary f_c and BW independently for these BPFs. In contrast, the tunable BPF that we propose here has a new feature that enables f_c and BW to be independently tuned.

The configuration of the proposed tunable BPF is shown in **Figure 2**. This BPF uses three resonators[*3] to construct a 3-stage filter that interconnects these resonators with each other and with the input/output ports by coupling circuits 1 to 4. Here, the number of stages is determined by the filter's performance requirements; it is not limited to three. Coupling circuits 1 to 4 have the role of transmitting the signal input at port 1 to each of the resonators and port 2. In addition, while coupling circuits 1 and 4 are transmission lines, coupling circuits 2 and 3 are lines each loaded with a Variable Capacitor (VC) 1 of capacitance C_1 thereby forming a variable phase shifter in which the phase shifting range[*4] can be varied according to the value of C_1. The reason for using a variable phase shifter in each of these coupling circuits is as follows. Coupling circuits 2 and 3 must each interconnect resonators at a phase

*2 **BPF**: A filter designed to extract signals in a specific frequency band from all signals.

*3 **resonator**: A circuit component having infinite or zero impedance at a specific frequency (resonant frequency).

*4 **phase shifting range**: The amount of change in a wave's phase.

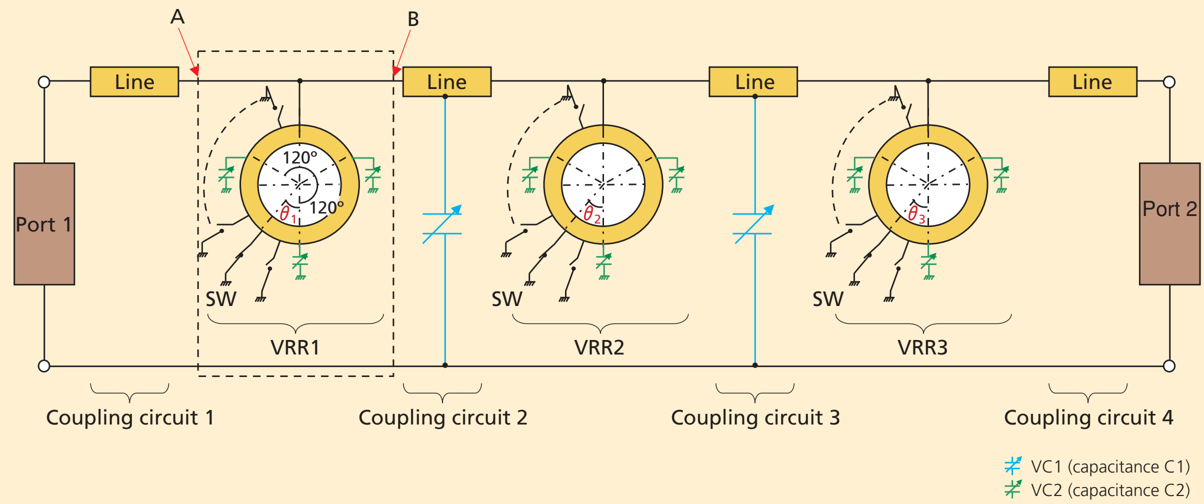

Figure 2 Tunable BPF circuit configuration

shifting range of 90° at frequency f_c, but if a simple line is used, they cannot do so at the designated phase shifting range when changing the BPF's f_c [5]. The key feature of this tunable-BPF circuit configuration is the use of a Variable Ring Resonator (VRR) consisting of a ring resonator, three equally spaced VC2 of capacitance C_2 and multiple SWs.

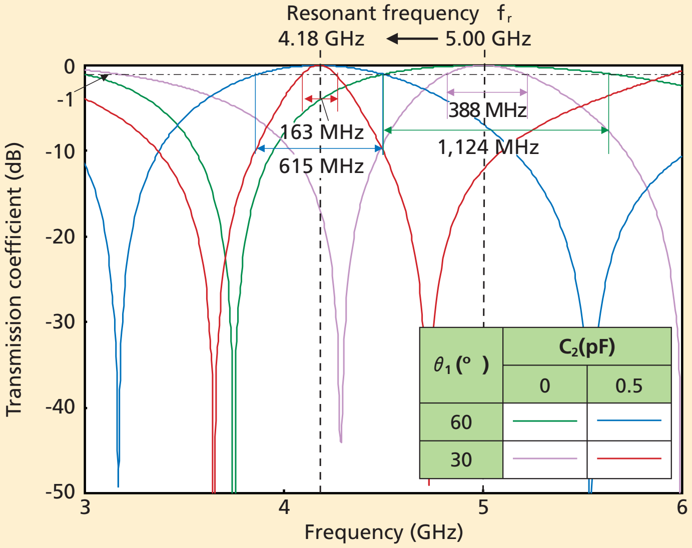

Figure 3 Frequency characteristics of VRR (calculated values)

2.1 VRR Characteristics

In this VRR, resonant frequency (f_r) changes by changing capacitance C_2 of VC2, while BW changes according to the state of SW connected between the ring resonator and a ground conductor[*5]. Here, at least one of the SWs connected to one ring resonator is in the ON state. Denoting the position of this SW in the ON state as θ, BW changes according to θ. **Figure 3** shows the results of calculating the frequency characteristics of the signal transmission coefficient[*6] for VRR1 from points A to B indicated by the broken line in Fig. 2. The length of this ring resonator in VRR1 is equivalent to one wavelength at 5.00 GHz, and since this VRR corresponds to an LC parallel resonator[*7], f_r is the frequency for which the transmission characteristics shown in Fig. 3 are maximum. Now, if the value of C_2 is increased from 0 pF to 0.5 pF, f_r changes from 5.00 GHz to 4.18 GHz. We can compare BW at 1 dB under the maximum transmission

*5 **ground conductor**: A conductor acting as a reference point for signal potential.

*6 **transmission coefficient**: Ratio of output power at the output port to input power at the input port computed as log10 (output power/input power) in units of dB.

*7 **LC parallel resonator**: A resonator that connects the inductor and capacitor in parallel and exhibits infinite impedance at the resonant frequency.

coefficient (1-dB BW). Specifically, if changing the value of θ in VRR1 (θ_1) from 60° to 30°, BW changes from 1,124 MHz to 388 MHz at f_r of 5.00 GHz and from 615 MHz to 163 MHz at f_r of 4.18 GHz. In both cases, BW narrows while keeping f_r constant. In short, this VRR can independently vary f_r and BW. Since the f_c and BW of this BPF is determined by the f_r and BW of each resonator, the use of VRRs here enable the configuration of a tunable BPF that can independently vary f_c and BW.

2.2 Tunable BPF Characteristics

Photo 1 shows our prototype tunable BPF based on the configuration shown in Fig. 2. It is achieved by forming a conducting film on a dielectric substrate and adopting a microstrip[*8] structure with ground conductors on the bottom surface of the substrate and signal lines on the top surface. Alumina ceramic is used for the dielectric substrate. The circular conductor on the inner side of the ring resonator is electrically connected by via holes to a ground conductor on the bottom surface thereby giving it the function of a ground.

To examine basic characteristics, a 100-μm-wide metal ribbon was used to make a connection between this ground conductor and the ring resonator with SW in the ON state in each VRR. No connection was made with the metal ribbon at these locations for SW in the OFF state. Angles θ_1, θ_2 and θ_3 in Photo 1 correspond to angles θ_1, θ_2 and θ_3 in Fig. 2 and represent θ of VRR1, VRR2 and VRR3, respectively. In addition, VC1 and VC2 are substituted by rectangular conductors (conductor patches) positioned near the inter-VRR lines and ring resonators, respectively. To increase the capacitance value, a 100-μm-wide metal ribbon was used to make a connection between a conductor patch and a ring resonator or inter-VRR line.

The results of measuring the characteristics of this tunable BPF are shown in **Figure 4**. In the figure, (a) shows the results for f_c of approximately 4.8 GHz and (b) the results for f_c of approximately 4.2 GHz. Measurement conditions and main characteristics are listed in **Table 1**. In this table, "ON" for VC1 and VC2 indicates the state in which a connection is made by a metal ribbon at the metal-ribbon connection locations shown together with VC1 and VC2 in Photo 1, while "OFF" indicates the state in which no connection by a

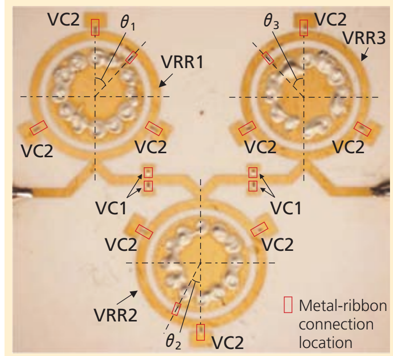

Photo 1 Prototype tunable BPF

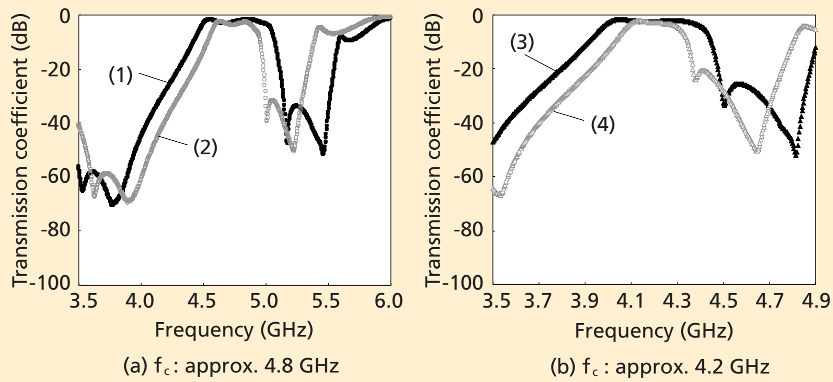

Figure 4 Tunable BPF frequency characteristics

Table 1 Tunable BPF measurement conditions and main characteristics

	VC1	VC2	θ_1, θ_3	θ_2	f_c	3-dB BW
(1)	OFF	OFF	36°	26°	4.76 GHz	554 MHz
(2)	OFF	OFF	26°	19°	4.75 GHz	336 MHz
(3)	ON	ON	43°	28°	4.19 GHz	503 MHz
(4)	ON	ON	34°	20°	4.20 GHz	252 MHz

*8 **microstrip**: A type of substrate structure using a high-frequency circuit.

metal ribbon is made at those locations.

From Fig. 4 and Photo 1, we can see that changing VC1 and VC2 from OFF to ON reduces f_c from approximately 4.8 GHz to 4.2 GHz. Next, for BW at 3 dB under the maximum value of the transmission coefficient (3-dB BW), we found that changing the value of each θ changes 3-dB BW by approximately 220 MHz for conditions (1) and (2) and by approximately 250 MHz for conditions (3) and (4) with f_c practically remaining the same in both cases. These results experimentally confirm that the tunable BPF achieved by the proposed configuration can independently vary f_c and BW.

As a future issue to be addressed, the prototype tunable BPF introduced here has a relatively large ring-line radius of 3.7 mm. The circuit must be downsized by some means, such as by applying a multi-layer substrate. Additionally, by designing and prototyping a tunable BPF using actual SWs and variable-capacitance devices, we plan to examine the characteristics of the proposed circuit including these devices and to solve problems that are consequently encountered.

3. Multi-band isolator

The transmit RF circuit uses a Duplexer (DUP) and isolator positioned between the PA and antenna (**Figure 5**). The isolator is an irreversible device featuring low loss in the direction from the PA to the antenna (incident wave in the figure) and high loss in the direction from the antenna to the PA (reflected wave in the figure). Since a signal input into the isolator from the antenna must pass through the DUP, the signal is not a receive signal but rather a reflected wave resulting from a transmit signal that returns from the antenna without being radiated. Antennas are usually designed to prevent the generation of reflected waves, but if a dielectric (such as a human body) happens to be near the antenna, impedance matching[*9] conditions change resulting in a reflected signal instead of a radiated one. A reflected wave that makes its way back to the PA can degrade characteristics and increase power consumption and even cause the PA to fail in some cases. An isolator is used to prevent these issues from happening.

3.1 Achieving a Multi-band Lumped-element Isolator

A lumped-element isolator[*10] frequently used in mobile terminals features three center conductors (L1 to L3 in **Figure 6**) on ferrite in a mutually intersecting manner with one end of one of these conductors grounded. A signal input from port 1 is propagated to port 2 while a signal input from port 2 is absorbed by resistor R1 connected to port 3. Each port is connected to a matching capacitance (capacitor) so as to obtain characteristics corresponding to operation in a specific frequency band. In existing mobile terminals, individual isolators adjusted to different frequency bands are arranged in parallel as shown in Fig. 1 (a). One method pro-

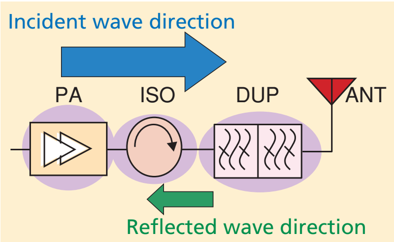

Figure 5 Configuration of transmit RF circuit

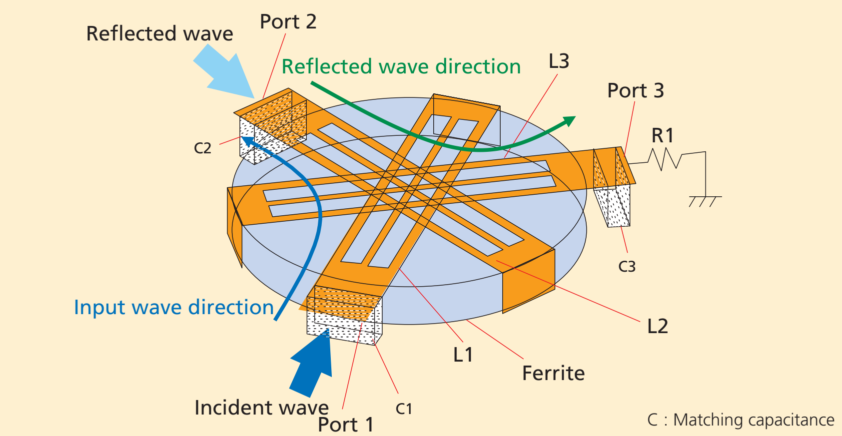

Figure 6 Lumped-element isolator

*9 **impedance matching**: The process of matching characteristic impedance on an electrical signal's transmit side with that on the receive side to prevent reflection loss along the transmission path.

*10 **lumped-element isolator**: An isolator consisting of lumped elements such as resistors, inductors and capacitors; the use of lumped elements promotes miniaturization.

posed for achieving a multi-band isolator varies the values of the three matching capacitances (C1 to C3) shown in Fig. 6 to control frequency characteristics [6]. This approach, however, requires variable-capacitance devices at each of the three ports, which can increase circuit size. In light of this issue, we proposed a method for controlling the frequency characteristics of the isolator using only one variable-capacitance device [7]. The equivalent circuit[*11] for the proposed isolator is shown in **Figure 7**.

3.2 Multi-band Isolator Characteristics Evaluation

We constructed a multi-band isolator using a varactor diode[*12] for the variable-capacitance device. An external view of this isolator is shown in **Photo 2** and a top view and side view of its configuration is shown in **Figure 8**. In this isolator, a reverse bias[*13] is applied to the varactor (applied voltage) to change capacitance and vary isolator characteristics. Frequency characteristics of Insertion Loss (IL) and Isolation Loss (ISOL) for varactor applied voltages of 0 V, 5 V and 20 V are shown in **Figure 9**. Here, IL means characteristics in the direction from PA to the antenna in Fig. 5 and ISOL means characteristics in the direction from the antenna to the PA as taken by the reflected wave generated at the antenna. A small IL indicates that the power amplified at the PA can be efficiently transmitted to the antenna, while a large ISOL indicates that the effects of reflected waves from the antenna can be mitigated.

The frequency bands for which IL < 1 dB and ISOL > 15 dB for each applied voltage are shown in **Table 2** together with minimum IL in each frequency band. These results show that the frequency band can be tuned from 1.69 GHz to 2.06 GHz if both of the above conditions are to be satisfied. Considering the states at each of these applied voltages, the operable band-

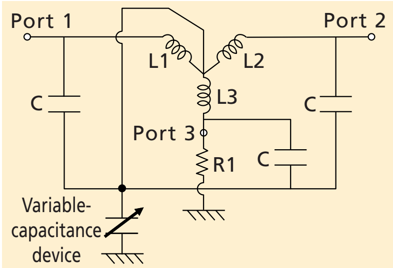

Figure 7 Equivalent circuit of proposed isolator

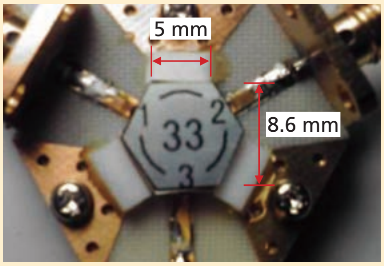

Photo 2 Proposed isolator

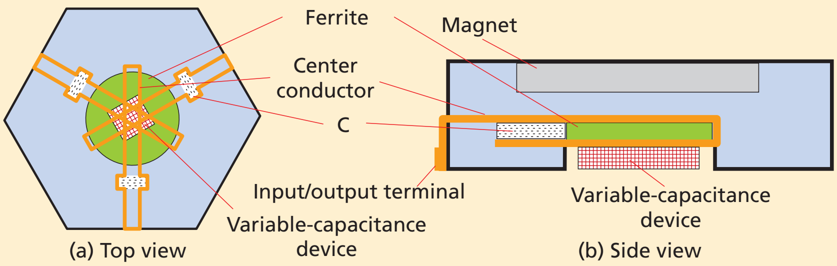

Figure 8 Configuration of proposed isolator

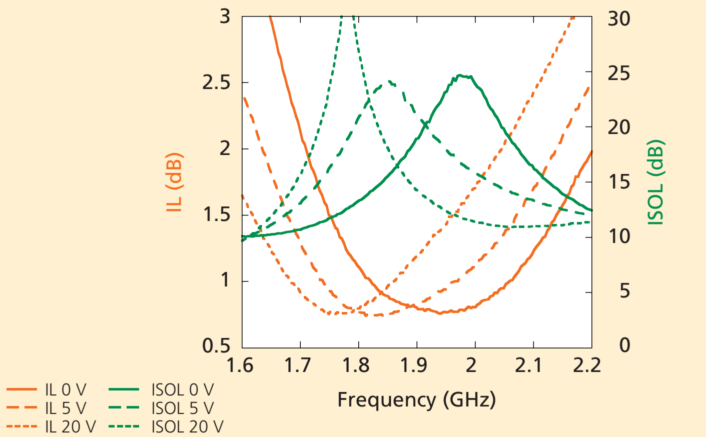

Figure 9 Frequency characteristics of multi-band isolator

*11 **equivalent circuit**: A technique for representing the electrical characteristics of a certain circuit by combining passive devices such as resistors, inductors and capacitors with a power source, current source, etc.

*12 **varactor diode**: A type of variable-capacitance device whose capacitance depends on the applied voltage.

*13 **reverse bias**: The application of voltage in a direction that minimizes current, or the application of negative voltage from the anode to the cathode in a diode.

Table 2 Characteristics of multi-band isolator in various states

Bias voltage	20 V	5 V	0 V
(A) Frequency range in which IL < 1 dB (GHz)	1.68-1.86	1.74-1.96	1.82-2.06
(B) Frequency range in which ISOL > 15 dB (GHz)	1.69-1.88	1.73-2.02	1.84-2.15
Frequency range satisfying both (A) and (B) (GHz)	1.69-1.86	1.73-1.96	1.82-2.06
Minimum IL (dB)	0.76	0.74	0.76

width of this prototype isolator is 370 MHz, which indicates that operable bandwidth can be increased compared to ordinary isolators having a bandwidth of about 100 MHz.

As a future issue, this prototype isolator needs to be further miniaturized since it is relatively large at 8.6 mm × 5 mm compared to isolators of about 2 to 3 mm square mounted in existing mobile terminals. Likewise, IL at the operable bandwidth is large at approximately 0.8 dB compared to the IL (approximately 0.3 to 0.5 dB) of isolators mounted in existing mobile terminals, so reducing this loss even further is a key issue.

4. Conclusion

We proposed a multi-band RF circuit to support the future increase in frequency bands and described techniques for converting the filter and isolator making up the RF circuit to multi-band devices. For the filter, we showed how the use of multiple SWs enabled center frequency and bandwidth to be independently varied, and for the isolator, we showed how using a varactor diode as a tunable capacitor, implementing it at one location, and varying its capacitance could expand the operating band.

To solve the remaining issues surrounding each device and provide expanded support for future frequency bands, we will continue our study on constructing a multi-band RF circuit that can adapt to a variety of frequency bands with one system.

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