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Unloaded Quality Factor for Hairpin Resonator Affected by Conduction and Radiation Losses on K-band

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Abstract

We investigate the effects of an Electroless Nickel Immersion Gold (ENIG) layer, the roughness of mat face on copper foil, and the radiation loss along a microstrip line and input/output coaxial connectors. The surface finishing process for planar circuits using a printed circuit board (PCB) is very important for preventing the corrosion of copper foil. There is a problem with coating the surface of copper foil because the conduction losses caused by the materials for surface finishing are higher than that of low-frequency bands. In addition, the roughness of the mat face on copper foil strongly affects the losses of the circuits at high frequencies. Moreover, radiation losses by coaxial connectors or some bonding methods like wire-bonding are a problem. In this paper, we distinguish some causes of losses in a hairpin resonator and a two-pole band-pass filter (BPF) by developing some theoretical equations and electromagnetic simulation models. Also, this verification is applied to the measured results of two-pole BPF. The effects of ENIG, copper roughness and radiation between coaxial connectors and a microstrip line on unloaded quality factor (Q_0) of the hairpin resonator are quantitatively revealed.

Keywords: Electroless Nickel Immersion Gold (ENIG), Roughness of Copper Foil, Hairpin Resonator, Conduction Quality Factor (Q_c), Dielectric Quality Factor (Q_d), Radiation Quality Factor (Q_r), Unloaded Quality Factor (Q_0), Band-pass Filter (BPF), Polytetrafluoroethylene (PTFE) Substrate

1. Introduction

Fifth-generation (5G) service for wireless communication will begin in 2020. The operating frequency from the K-band (18–26 GHz) to the Ku-band (26–40 GHz) will be the target frequency band.[1] Circuits using printed circuit boards (PCB) are more important for radio frequency (RF) circuits, baseband circuits, and many other circuits in 5G service. When these circuits are used in severe environments, pure copper foil is corroded by oxidization and moisture in atmosphere. Therefore, surface finishes on the pattern of copper foil are necessary to prevent the oxidation. Table 1 shows some kinds of surface finishes.[2, 3] Shelf time means shelf life. Also, the Relative Cost Adder in Table 1 defines the cost factor of only surface finishing. [2] If this cost factor is higher, the production cost is higher. Generally, the hot air solder process with Sn/Pb solder or Pb-free solder is a popular process because of its good solderability and low-cost process. However, in the case of circuits on a higher frequency, the electrical characteristics will be worse, since the flatness of the layers of

Sn/Pb solder or Pb-free solder is coarse. Here, we focus on the process of Electroless Nickel Immersion Gold (ENIG) because of its flat surface, good solderability, long shelf time, and relatively lower product cost. The ENIG process is an electroless plating process. In a general process, the thicknesses of Ni-P and flash gold layers are about 3 μm and less than 50 nm, respectively.[3]

Yoshitomi[4] showed the relative conductivity in the case of Ni/Au layers of a microstrip line composed of Polytetrafluoroethylene (PTFE) substrate made by Arlon, Inc. They showed the relative conductivity affected by Ni/Au layers at 20 GHz is less than 30% compared with pure copper foil. That means there is no candidate for PCB passivation beyond the K-band possessing low surface resistance. In addition, the roughness of the mat face on copper foil is caused by high transmission loss beyond the K-band. The mat face of copper foil refers to the boundary between the copper foil and the dielectric material. Generally, the roughness of electrodeposited (ED) copper foil is equal to 1.8 μm , which is 4.5 times the skin depth at 20 GHz.[5]

Table 1 Characteristics of surface finishes.

Material	Types of surface finishings	Thickness (μm)	shelf time (month)	Relative Cost Adder
Benzotriazole-system, Imidazole-system (Organic)	Organic Solderability Preservative	0.01 to 0.4	about 6	1.0
Sn/Pb	Hot Air Soder Level	0.762 to 38.1	12	1.0
Pb Free solder	Hot Air Soder Level	0.762 to 38.1	12	1.0
Ag	Immersion Silver	0.203 to 0.381	6 to 12	1.1
Sn	Immersion Tin	0.203 to 0.381	6	1.1
Ni/Au	Electrolytic Ni/Au	0.127 to 0.381 (Gold Flash)	12	3.5
Ni-P/Pd/Au	Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG)	Ni-P: 3.05 to 6.09, Pd: 0.101 to 0.508, Au: 0.05 to 0.203	12	2.5
Ni-P/Au	Electroless Nickel Immersion Gold (ENIG)	Ni-P: 3.05 to 6.09, Au: 0.05 to 0.203	12	1.1

Radiation losses by patterned input/output feed lines and some coaxial connectors are also a problem. Moreover, it is necessary to reduce radiation losses through resonator shape in a band-pass filter (BPF). A hairpin resonator on the K-band has many positive features, including a compact structure and lower radiation loss than with a half-wave straight-type resonator. It is possible to reduce the radiation loss on the K-band for a hairpin resonator to about one tenth compared with that of a half-wave straight-type resonator by optimizing the thickness of the substrate and the size of the line and space of the hairpin resonator. Therefore, hairpin resonators are used for various high-frequency filters. These losses are related to an attenuation constant α , which is a real part of the propagation constant for γ and used for discussing the performance of transmission lines. Unloaded factor Q_0 is inversely proportional to α and a very important factor for determining the loss performances of various high-frequency filters. That means filters using resonators with a high Q_0 produce low insertion loss and high performance.

In this paper, firstly, conduction quality factor Q_c , dielectric quality factor Q_d , radiation quality factor Q_r , and Q_0 for the hairpin resonator are defined using equations. Q_c and Q_d are quality factors based on conductor loss and dielectric loss, respectively. Q_r is also a quality factor based on radiation loss caused from the shapes of a circuit pattern and the boundary structure between the circuit pattern and coaxial connector, and so on. Secondly, two-pole BPF at 20 GHz using hairpin resonators is configured and fabricated for investigating the effects of ENIG, the surface

roughness on copper foil, and radiation by input/output feed lines and some coaxial connectors. Although it is common sense that conduction and radiation losses are degraded by those factors, there is no paper which quantitatively analyzed them using theoretical equations, electromagnetic (EM) simulation and measurement. Finally, the effects of ENIG, copper roughness and radiation between coaxial connectors and the microstrip line on the Q_0 of the resonator are quantitatively revealed.

2. Theoretical Verification of Q_c , Q_d , Q_r and Q_0 for Hairpin Resonator

2.1 Q_c , Q_d , Q_r and Q_0 in case of pure copper foil with the surface roughness of zero thickness

The structure of a hairpin resonator was discussed in [6]. Figure 1 shows an electromagnetic (EM) simulation model for verification of theoretical Q_0 . The dimensions of a hairpin resonator for calculations of Q_c , Q_d , Q_r and Q_0 using some equations are the same as those shown in Fig. 1. Also, the substrate for the hairpin resonator is assumed to be Polytetrafluoroethylene (PTFE) substrate, whose dielectric constant, $\tan\delta$ and PTFE substrate thickness are 2.2, 0.0007 and 0.254 mm, respectively. Moreover, the conductivity and thickness of the copper foil on substrate are 5.8×10^7 S/m and 18 μm . The respective equations for Q_c , Q_d , Q_r , Q_0 and α are as follows:[7]

$$Q_c = 10.965 \frac{Z_c^a h(mm)}{R_{s,r} A} \sqrt{f(GHz)} \quad (1)$$

$$Q_d = \frac{\epsilon'_r + 1 + (\epsilon'_r - 1) \left(1 + \frac{10h}{W}\right)^{-0.5}}{\epsilon'_r \tan \delta_\epsilon \left\{1 + \left(1 + \frac{10h}{W}\right)^{-0.5}\right\}} \quad (2)$$

$$Q_r = 2\pi \frac{P_{in}}{P_{rad}} = \frac{Z_c}{2\sqrt{\frac{\mu_0}{\epsilon_0}} F_{1,2} \left(\frac{h}{\lambda_0}\right)^2} \quad (3)$$

$$Q_0 = \frac{1}{\left(\frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r}\right)} \quad (4)$$

$$\alpha_x = \frac{\beta}{2Q_x} = 8.686 \frac{\pi \sqrt{\epsilon_{eff}}}{Q_x \lambda_0} (dB/m) \quad (x = c, d, r \text{ and } 0) \quad (5)$$

$$\alpha_0 = \alpha_c + \alpha_d + \alpha_r \quad (6)$$

$$\epsilon_{eff} = \frac{\epsilon'_r + 1}{2} + \frac{\epsilon'_r - 1}{2} \left(1 + \frac{10h}{W}\right)^{-\frac{1}{2}} - \frac{\epsilon'_r - 1}{4.6} \frac{t/h}{\sqrt{W/h}} \quad (7)$$

Table 2 shows the parameters for Eqs. (1) – (7). Q_r is predicted by the results of [8] because P_{in}/P_{rad} in the equation of Q_r is difficult to theoretically define. The values of Q_c , Q_d , Q_r , Q_0 , α_c , α_d , α_r and α_0 for a surface roughness of zero on copper foil are shown in Table 3. The ϵ_{eff} for calculating α_x ($x = c, d, r$ and 0) is equal to 1.87, which is determined using Eq. (7). The calculated Q_0 from Eq. (4) for the hairpin resonator is 245. Also, the ratio of attenuation constants by conductor, dielectric material and radiation are

Fig. 1 EM simulation model for calculating Q_0 .

shown in Table 3. It was found that the conductor loss of the hairpin resonator at 20 GHz is most dominant.

The calculated theoretical Q_0 using EM simulation will need to be verified. Sonnet ver. 15. 52 is used for EM simulation of Fig. 1. The conductor and dielectric models for EM simulation are assumed to be copper and PTFE substrate, respectively. The conductivity and thickness of copper are 5.8×10^7 S/m and 18 μm . Also, the thick metal model (TMM) for two sheets is used as the conductor model. TMM means a conductor model which is able to consider physically thick planar metal.[9] The simulated results of conduction loss for two sheets are accurate

Table 2 Parameters of Equations (1) to (7).

Parameters	Description
Z_a^c	Characteristic impedance in the case of air medium.
h	Thickness of dielectric substrate
f	Frequency
$R_{s,r}$	Normalized resistance by copper
A	Theoretical conductor attenuation factor[11]
ϵ'_r	Real part of dielectric constant for substrate
W	Line width of copper on top side of substrate
$\tan \delta_\epsilon$	Dielectric tangent for substrate
P_{in}	Input power
P_{rad}	Radiation power
Z_c	Characteristic impedance in the case of dielectric medium
μ_0	Permeability in air
ϵ_0	Permittivity in air
$F_{1,2}$	Radiation factor
λ_0	Wavelength in air
β	Phase constant for transmission line
ϵ_{eff}	Effective dielectric constant
α_c	Attenuation constant caused by conduction loss
α_d	Attenuation constant caused by dielectric loss
α_r	Attenuation constant caused by radiation loss
α_0	Attenuation constant caused by total loss

Table 3 Q_c , Q_d , Q_r , Q_0 , α_c , α_d , α_r and α_0 for zero surface roughness of copper foil.

	Q_c	Q_d	Q_r	Q_0
	388	1,802	1,053	245
	α_c (dB/m)	α_d (dB/m)	α_r (dB/m)	α_0 (dB/m)
	6.2	1.3	2.3	9.9
	$(\alpha_c/\alpha_0) \times 100$ (%)	$(\alpha_d/\alpha_0) \times 100$ (%)	$(\alpha_r/\alpha_0) \times 100$ (%)	
	63.2	13.6	23.2	

Zero surface roughness copper foil
(Theoretical values)

Table 4 Q_c , Q_d , Q_r and Q_o for zero surface roughness of copper foil by EM simulation.

	Q_c	Q_d	Q_r	Q_o
Zero surface roughness copper foil (EM Simulation)	264	2,000	1,020	190
	α_c (dB/m)	α_d (dB/m)	α_r (dB/m)	α_o (dB/m)
	9.5	1.3	2.5	13.3
	$(\alpha_c/\alpha_o) \times 100$ (%)	$(\alpha_d/\alpha_o) \times 100$ (%)	$(\alpha_r/\alpha_o) \times 100$ (%)	
	71.4	9.8	18.8	

Table 5 Q_c , Q_d , Q_r and Q_o for surface roughness on mat face of 1.8 μm (RMS).

	Q_c	Q_d	Q_r	Q_o
Mat face roughness of 1.8 μm (RMS) (Theoretical values)	197	1,802	1,053	152
	α_c (dB/m)	α_d (dB/m)	α_r (dB/m)	α_o (dB/m)
	12.3	1.3	2.3	15.9
	$(\alpha_c/\alpha_o) \times 100$ (%)	$(\alpha_d/\alpha_o) \times 100$ (%)	$(\alpha_r/\alpha_o) \times 100$ (%)	
	77.2	8.4	14.4	

excluding the case of very tightly coupling between coupled lines below the conductor thickness.[9] The dielectric constant, $\tan\delta$ and thickness of PTFE substrate are 2.2, 0.0007 and 0.254 mm. Table 4 shows the calculated Q_o and α from the frequency characteristics by Sonnet. The effective dielectric constant for calculating α_x ($x = c, d, r$ and o) is 1.91 at 20 GHz, which was calculated by Sonnet. The difference of Q_o between the theoretical values (Table 3) and electromagnetic simulation is about 22.5%. These results show that theoretical verification is good for estimating Q_c , Q_d , Q_r and Q_o in advance of EM simulation. It is an especially useful method for approximate design, since verification using theoretical equations is faster, simpler and more flexible. The effects of a rough surface copper foil and ENIG will be verified using this method.

2.2 Q_c , Q_d , Q_r and Q_o in the case of pure copper foil considering the roughness of the mat face

The roughness on the mat face of copper foil for a PTFE substrate is 1.8 μm in the case of electrodeposited (ED) copper foil [5]. Figure 2 shows a cross-section of PCB with ED copper foil. The mat face of the copper foil indicates the boundary between the copper foil and dielectric material while the other side indicates a shiny face. There are many kinds of models for the rough surface of a conductor, for example, the Morgan, Hammerstad and Jensen (NHJ) model,[10, 11] the snowball model,[12] and so on. In this study, the MHJ model is used for modeling the mat face. The key feature of the MHJ model is that it is simple and basic for conductor roughness. The electrical influence of conductor roughness can be considered by calcu-

Fig. 2 Cross-section of PCB with ED copper foil.

lating the attenuation constant using the values of the root mean square (RMS) of conductor roughness and skin depth for the operating frequency. Although another model is probably more accurate than the MHJ model, it is needed for the detailed shape and dimensions of the boundary between the conductor and the dielectric material of the PCB using Scanning Electron Microscopy (SEM) or Transmission Electron Microscopy (TEM). The equation for the attenuation constant with the MHJ model is as follows:

$$\alpha_{rough}(\Delta) = \alpha_{smooth} \left[1 + \frac{2}{\pi} \arctan \left\{ 1.4 \left(\frac{\Delta}{\delta} \right)^2 \right\} \right]. \quad (8)$$

$\alpha_{rough}(\Delta)$ shows the attenuation constant considering roughness of Δ , which is the RMS of the conductor roughness. α_{smooth} and δ show the attenuation constant in the case of zero roughness and skin depth for metal at the operating frequency, respectively. The values of Q_c , Q_d , Q_r and Q_o for Δ on the mat face of 1.8 μm are shown in Table 5. Also, the ratios of the attenuation constants by conductor, dielectric material and radiation are shown in Table 5.

Table 6 α_{c_Cu} and α_{c_ENIG} for references [4], [18] and [19].

Author	α_{c_Cu} (dB/m)	α_{c_ENIG} (dB/m)	$\alpha_{c_ENIG} / \alpha_{c_Cu}$
Yoshitomi [4]	31	36	1.16
Coonrod [18]	21	26	1.24
Huber [19]	36 @25 mm	44 @25 mm	1.22

Table 7 Q_c , Q_d , Q_r and Q_o for ENIG on surface roughness on mat face of 1.8 μm .

	Q_c	Q_d	Q_r	Q_o
ENIG / rough copper foil in the case of 1.8 μm (Theoretical values)	164	1,802	1,053	132
	α_c (dB/m)	α_d (dB/m)	α_r (dB/m)	α_o (dB/m)
	14.7	1.3	2.3	18.4
	$(\alpha_c / \alpha_o) \times 100$ (%)	$(\alpha_d / \alpha_o) \times 100$ (%)	$(\alpha_r / \alpha_o) \times 100$ (%)	
	80.2	7.3	12.5	

The Q_c is almost half of the value compared with that of zero roughness (Table 3) because α_c is degraded until about twice at 20 GHz in the case of 1.8 μm roughness. The Q_o in the case of considering the mat face roughness is 62% compared with that of zero roughness.

2.3 Q_c , Q_d , Q_r and Q_o in the case of ENIG/rough mat face of copper foil

Staiculescu[13] showed the synthesized attenuation constant and surface resistance for Nickel and Copper foil. This method is effective for calculating the attenuation constant with Ni/Au layers. Also, Deng[14] and Curran[15] have defined the effective skin depth, propagation constant and characteristic impedance for a multilayer coated conductor. However, it is difficult to determine the parameters of conductivity and magnetic permeability because the physical parameters of Ni-P alloy for high frequencies depend on the measurement method and operating frequency.[16–18] Therefore, the effects of ENIG are predicted from the measured results in previous research. Table 6 shows the attenuation constants for only copper foil (α_{c_Cu}) and ENIG (α_{c_ENIG}) which were extracted by the measured or calculated transmission characteristics in three papers.[4, 18, 19] These results show the ratio of α_{c_Cu} and α_{c_ENIG} is almost in agreement, which is about 1.2. The Δ of the mat face of copper foil is equal to 1.8 μm in Table 7. When Q_c and Q_o are calculated from the extracted ratio of α_{c_Cu} and α_{c_ENIG} , Q_c and Q_o are equal to 164 and 132, respectively. In Ref.,[20] there is a case in which the measured insertion losses at 20 GHz by copper and ENIG have an inverse relationship with the general cases. There is a possibility to degrade performance by oxidation of pure copper. If this is compared with the inser-

Table 8 Design specification of two-pole BPF.

Center frequency of f_o (GHz)	20
Passband bandwidth of BW (GHz)	1
Fractional bandwidth of FBW (%)	5
Passband ripple (dB)	0.022
Minimum return loss in passband (dB)	22.97
Insertion loss of IL (dB)	1.65

tion losses by EM simulation for pure copper and measurement for ENIG, the ratio of them is about 1.02. Also, Ref. [21] shows RF resistances by five kinds of surface finish process. The ratio of the calculated power at 20 GHz of copper and ENIG are around 1.33. Therefore, the calculated Q_c and Q_o are reasonable since it is almost agreement with this verification.

3. Design of Two-pole BPF

The design specification of two-pole BPF is shown in Table 8. The dielectric substrate is assumed to be PTFE substrate, whose dielectric constant and $\tan\delta$ are equal to 2.2 and 0.0007, respectively. Figure 3 shows the calculated characteristic functions using g -parameters for Chebyshev-type two-pole BPF based on the design specifications of Table 8. The design specification of IL is determined based on Q_o , which is equal to 132. Conductivity for the ENIG conductor model in Sonnet is determined by EM simulation results for only a hairpin resonator. This value is not only the physical parameter but also the fitting parameter. Although the dielectric model for electromagnetic simulation is similar to that of section 2, the conductivity and thickness of the conductor model is determined to $4.0 \times$

Fig. 3 Calculated frequency characteristics for Chebyshev-type two-pole BPF by design specification.

Fig. 4 The layout of two-pole BPF.

Fig. 5 The simulation results of Fig. 4.

10^7 S/m and $21.05 \mu\text{m}$. The configured structure of two-pole BPF using a conventional design procedure of BPF and Sonnet is shown in Fig. 4. Figure 5 also shows the simulated results of the presented BPF. It is almost in agreement with the frequency characteristics of Fig. 3.

4. Fabrication and Measurement of Two-pole BPF

4.1 Fabrication and measurement of two-pole BPF using hairpin resonators

An image of fabricated two-pole BPF is shown in Fig. 6. It is fabricated by a commercial wet etching process. Figure 7 shows the compared results with EM simulation and measurement for two-pole BPF. Table 9 shows the main

Fig. 6 Image of fabricated two-pole BPF.

Fig. 7 Comparison with EM simulation and measurement for two-pole BPF.

Table 9 Measured results for two-pole BPF.

Parameters	simulation	Measurement
f_0 (GHz)	19.99	20.2
BW (GHz)	1.054	1.28
FBW (%)	5.27	6.34
IL (dB)	1.54	3.85

parameters for EM simulation and measurement for two-pole BPF. The measured results are acquired by an E8364B vector network analyzer (VNA). The VNA is calibrated using mechanical SOLT kits before measurement. 2.4-mm coaxial connectors are used as the interface of the VNA and two-pole BPF. The IL for measured results is higher than that for EM simulation. When Q_0 is estimated by IL for measured results, it is equal to 42.65.

4.2 Effects of conductor and radiation losses for input/output feed lines and radiation loss for 2.4 mm connectors

Figure 8 shows the compared results in the cases of de-embedding or not de-embedding the effects of input/output feed lines and input/output coaxial connectors. When the effects of input/output feed lines and coaxial connectors are removed using the method by Tomita,[22] IL by de-embedding input/output feed lines is 1.31 dB lower than that of the not de-embedding one. Firstly, the effects of input/output feed lines are excluded by de-embedding them. Secondly, scattering parameters transform to a two-

port short-circuit admittance matrix. Finally, that is transformed to a coupling matrix, which is expressed by resonant frequencies, coupling coefficients, external quality factors of BPF and unloaded quality factors of resonators. [22] It is a very effective extraction method. Higher insertion loss means that conduction losses by 2.4-mm connectors and input/output feed lines and radiation losses among 2.4-mm connectors and input/output feed lines are equal to 1.31 dB. The average Q_0 of two-pole BPF after removing those effects is equal to 60.68. This value is not in agreement with Q_0 (it is equal to 42.65.) calculated by the IL of two-pole BPF. It is considered that those causes occur because of radiation along the microstrip lines and 2.4-mm connectors. The relationship of P_{rad}/P_{in} for radiation along the microstrip lines and coaxial connector is shown in [7, 23]. P_{rad} and P_{in} show the radiation and input power, respectively. The equations for Q_r are defined as follows:

$$Q_{r_2.4mm\ connector} = 2\pi \frac{P_{in}}{P_{rad}} = 2\pi \frac{9}{4Z_c} \left\{ \frac{\lambda_0 h}{(r_b - r_a)r_a} \right\}^2$$

$$= \pi \frac{9\lambda_0^2 h^2}{2Z_c \{(r_b - r_a)r_a\}^2} \quad (9)$$

$$Q_{r_total} = \frac{1}{\frac{1}{Q_{r_2.4mm\ connector}} + \frac{1}{Q_{r_2.4mm\ connector}} + \frac{1}{Q_{r_BPF}}}, \quad (10)$$

Fig. 8 Compared results in cases of de-embedding or not de-embedding the effects of input/output feed lines and coaxial connectors.

where r_a and r_b indicate the inner and outer radii of the coaxial connector, respectively. The other parameters are the same as Table 2. In Eq. (10), Q_{r_BPF} indicates the radiation quality factor Q_r in Table 7, which is equal to 1,053. When Q_{r_total} is calculated using Eqs. (9) and (10), it is equal to 62.63. Equation (4) indicates that the additive law of reciprocal each quality factor is established. Therefore, Eq. (10) is also established even if the causes of Q_r in the BPF are complicated. There are two reciprocal terms of $Q_{r_2.4mm\ connector}$ in Eq. (10) since two 2.4-mm connectors are used in two-pole BPF. Q_c , Q_d , Q_{r_total} and Q_0 for ENIG on copper with 1.8- μ m roughness on the mat face adds the effects of radiation from two 2.4-mm connectors are shown in Table 10. Also, Table 10 shows the ratio of α_c , α_d and α_{r_total} in the case of considering radiation losses among input/output feed lines and 2.4-mm connectors. There is almost agreement with Q_0 estimated by IL for the measured results of two-pole BPF. It was found that the effect of radiation between a microstrip line and a coaxial connector is not neglected when the coaxial connector is used as the interface of the planar circuit.

Finally, Fig. 9 shows the bar graph of α_c , α_d , α_r and α_0 in each condition shown in Tables 3, 5, 7 and 10, respectively. It was found that the roughness on the mat face strongly

Fig. 9 Comparison of α_c , α_d , α_r and α_0 in each condition shown in Tables 3, 5, 7 and 10.

Table 10 Q_c , Q_d , Q_{r_total} and Q_0 for ENIG on copper with 1.8- μ m roughness on mat face adding the effects of radiation from two 2.4-mm connectors.

	Q_c	Q_d	Q_{r_total}	Q_0
ENIG / rough copper foil in the case of 1.8 μ m adding the effects of radiation from two 2.4 mm connectors (Theoretical values)	164	1,802	63	44
	α_c (dB/m)	α_d (dB/m)	α_{r_total} (dB/m)	α_0 (dB/m)
	14.7	1.3	38.6	54.7
	$(\alpha_c/\alpha_0) \times 100$ (%)	$(\alpha_d/\alpha_0) \times 100$ (%)	$(\alpha_r/\alpha_0) \times 100$ (%)	
	26.9	2.5	70.6	

affected Q_c . Although it is better to use rolled copper foil, its known tensile strength is weaker than that of ED copper foil. Recently, some kinds of ED copper foils which are relatively lower loss, strong tensile strength and low cost have been realized.[24] It is important to select a PCB considering cost and performance. The improvement of Q_c affected by ENIG is very difficult if only using the standard process for ENIG. If raising the product cost is allowed, it is very effective to optimize the thickness of gold and Ni-P alloy layers or change the material for the bonding metal. The radiation between a microstrip line and a coaxial connector should be suppressed for improvement of Q_r . For instance, using electromagnetic shields around coaxial connectors has been considered. Although it is effective using a ground-signal-ground (GSG) probe for measurement, using coaxial connectors is inevitable if discrete BPF is needed for system design at the level of a RF frontend system. Therefore, it is important to improve the structure to include an electromagnetic shield and coaxial connectors without the occurrence of unwanted resonances by TE or TM modes.

5. Conclusion

We quantitatively investigated the effects of an Electroless Nickel Immersion Gold (ENIG) layer, the roughness of mat face on copper foil, and the radiation loss along a microstrip line and coaxial connectors using some theoretical equations, EM simulation and measured results. The verified results using some equations were almost in agreement with Q_0 estimated by IL for the measured results of two-pole BPF using hairpin resonators. It is shown that those results are effective for BPF design on the K-band. In future work, the accuracy of the theoretical values will be raised and suppression methods for the effects of conduction and radiation losses will be proposed.

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