Adaptive Compensation Method for the Temperature Dependence of RF Transformer Isolation

Takanobu Aoyama*, Yoshiki Shibata*, Tomohiko Kanie**, Yuichi Noro* and Takashi Takeo†

Abstract – In this study, we propose an adaptive compensation method for the temperature dependence of RF transformer isolation and present results of preliminary experiments. First of all, we examine the isolation temperature dependence of an RF transformer designed as a splitter, by means of both an electromagnetic simulation technique and experiments, to show the significance of the present issue. Then, we discuss the nature of a transformer core so as to obtain the most desirable isolation characteristics against a temperature change. Finally, in order to adaptively compensate for the isolation variation due to temperature, we propose a bias current superimposed on the RF signal, where the current amplitude is adjusted according to temperature change, and demonstrate the results of preliminary experiments conducted at a fixed temperature, but with different bias currents, indicating the validity of the proposed method.

Keywords: Compensation, Temperature dependence, RF transformer, Isolation

1. Introduction

Ferrite is used in many RF devices, such as a transformer, as a key component [1], [2]. For example, when designing an RF transformer, which is a typical RF device and uses ferrite as its core material, one has to know the temperature dependence of the material so as to realize the desired performance of the device, since ferrite permeability is affected by temperature.

Among the performance characteristics of an RF transformer, isolation has been found by previous study to have the most significant temperature dependence [3]. Therefore, in this study, we deal with the temperature dependence of the isolation and discuss a method for alleviating it. To begin with, we investigate the relationship between the isolation characteristics and nature of the ferrite core (i.e. size and permeability) in order to find a core suitable for suppressing the variation in isolation due to temperature. Then, an adaptive compensation method for improving the temperature dependence of transformer isolation by utilizing the superimposing of direct bias current, is proposed. The results of preliminary experiments are also demonstrated.

2. RF Splitter and its Isolation

2.1 RF Splitter

An RF splitter consisting of transformers has one input and multiple outputs and acts to deliver input power to the outputs. A transformer, in turn, consists of a ferrite core with a few turns of windings. As an example, Fig. 1 illustrates a circuit of a 2-way splitter which has one input and two output ports. The performance of a splitter is generally designated by loss $L$ and isolation $IL$, which are defined as the transmission from Port 1 to Port 2 or Port 3 and that from Port 2 to Port 3 or from Port 3 to Port 2, respectively. These two performance factors are given in decibels by

\[
L = 20 \log(S_{21}) \text{ or } 20 \log(S_{31}) \\
IL = 20 \log(S_{32}) \text{ or } 20 \log(S_{23}),
\]

where $S$ denotes a scattering parameter [4].

![Fig. 1. 2-Way splitter circuit.](image-url)
2.2 Temperature Dependence of Ferrite Core Permeability

Ferrite permeability is known to have a frequency dependence known as dispersion and can be approximated as a function of frequency as follows.

\[ \mu = 1 + \frac{\chi_{rs}}{1 + \omega^2 \tau^2} - j \frac{\chi_{rs} \omega \tau}{1 + \omega^2 \tau^2} = \mu' - j \mu'', \]  

where \( \omega \) is the angular frequency, \( \chi_{rs} \) is the magnetic susceptibility, \( \tau \) is the relaxation time, and \( \mu' \) and \( \mu'' \) are the real and imaginary parts of permeability, respectively.

Besides the frequency dependence mentioned above, ferrite permeability is affected by temperature. In designing an RF device, such as a transformer, using ferrite, one has to measure the material’s permeability at high frequencies and various temperatures. However, this measurement has not always been easy to take. In this study, we have measured this permeability temperature dependence using a combined microstrip line circuit-coaxial conductor method [5], which is suitable for that purpose on account of the small heat capacity of the measurement circuits.

Examples of the results of the temperature dependence measured using the above circuits are demonstrated in Fig. 2, where the temperature has been varied from –10 °C to 80 °C in 30 °C steps. From Fig. 2, one can see that both the real and imaginary parts of the permeability dispersion curves shift towards lower frequencies as the temperature increases.

In order to investigate the quantitative relationship between the permeability \( \mu \) and the temperature \( T \) (K), we have determined the temperature dependence of the relaxation time \( \tau \) and the magnetic susceptibility \( \chi_{rs} \). Plotting the logarithm of the relaxation time \( \tau \) as a function of \( 1/T \), it has been found that between –10 °C and 50 °C the two quantities can be linearly related as

\[ \ln(\tau) = C_1 (1/T) + C_2, \]  

where \( C_1 = -2280 \) and \( C_2 = 5.24 \).

Likewise, values of the static magnetic susceptibility \( \chi_{rs} \) were estimated from the results in Fig. 2 and plotted as a function of temperature, revealing that at temperatures lower than the Curie temperature (100°C) of the sample material, the above two variables can also be linearly related as

\[ \chi_{rs} = C_3 T + C_4, \]  

where \( C_3 = 14.6 \), and \( C_4 = -2570 \). Utilizing equations (3) and (4), we can predict the permeability dispersion at any temperature under practical circumstances.

2.3 Isolation Variation due to Temperature

Using the measurement results for the ferrite permeability dependence on temperature obtained in the previous subsection, we have calculated a temperature dependence of an RF transformer isolation by means of an electromagnetic simulation. Parameters used in the simulation are listed in Table 1 and the results are illustrated in Fig. 3.

As can be seen from Fig. 3, the transformer isolation becomes worse according to the temperature, ranging from –24 dB to –12 dB in this case.

Experiments corresponding to the calculation were also done and the results are illustrated in Fig. 4, showing the isolation variation ranging from –24 dB to –8 dB, which is similar to the simulation results.

Fig. 2. Experimental results for permeability temperature dependence.
### Table 1. Parameters of the core used in the calculation

<table>
<thead>
<tr>
<th>Core inner diameter</th>
<th>Core outer diameter</th>
<th>Core length</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 mm</td>
<td>3.5 mm</td>
<td>4 mm</td>
<td>2000</td>
</tr>
</tbody>
</table>

![Fig. 3. Calculated results for the isolation variation due to temperature.](image)

3. **Dependence on Core Permeability and Length**

#### 3.1 Core Permeability Dependence

The transformer isolation is considered to be dominated by the loss mechanism of electromagnetic power in the core. In other words, the isolation may be in close relation to the loss factor (\(\tan\delta = \mu''/\mu'\)) of the material’s permeability. Fig. 5 and Fig. 6 show the loss factor vs. the frequency and the isolation vs. the frequency, respectively, calculated for three different cores having the material parameters listed in Table 2. The inner and outer diameters of these cores were assumed to be 0.7 mm and 3.5 mm, respectively, and the length was 6 mm. The calculated results indicate that the above inference about the relationship between the loss factor and the isolation is right and the isolation improves according to the increase in \(\tan\delta\).

![Fig. 5. Permeability dependence of the loss factor.](image)

### Table 2. Material parameters of the cores

<table>
<thead>
<tr>
<th>Core</th>
<th>Initial permeability</th>
<th>Resonance frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core 1</td>
<td>100</td>
<td>60 MHz</td>
</tr>
<tr>
<td>Core 2</td>
<td>500</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Core 3</td>
<td>2000</td>
<td>3.5 MHz</td>
</tr>
</tbody>
</table>

![Fig. 6. Permeability dependence of the isolation.](image)

#### 3.2 Core Length Dependence

The temperature dependence of the isolation would also be affected by the core shape or size. Thus, we have calculated the transformer isolation for ferrite cores having the same material parameters as Core 2 in Table 2, but different lengths from 2 mm to 8 mm.

In Fig. 7, the isolations calculated for core lengths of 2 mm to 8 mm and a constant temperature of 20 °C are plotted as a function of frequency. As can be seen, when the core length is short (2 mm), the isolation is worse (about -12 or -13 dB). The isolation improves as core length increases, i.e.
its absolute value in decibel becomes larger. However, it degrades again as the core exceeds 7 mm in length. It can be seen from Fig. 6 that the optimum core length for obtaining the best isolation is approximately 6 mm. If the ambient temperature is other than 20 °C, the results of the isolation dependence on the core length would be different. To illustrate this, we have made similar calculations at various temperatures and taken the average on the isolation over the whole temperature range (-10°C to 80°C). This averaged isolation and its deviation due to temperature are shown as a function of the core length in Fig. 8. One can appreciate that the optimum core length for obtaining the most preferable isolation characteristics (on the average) is also about 6 mm.

![Fig. 7. Isolation dependence on core length.](image)

![Fig. 8. Averaged isolation and its deviation due to temperature.](image)

4. Adaptive Compensation

4.1 Bias Current Superimposing

As mentioned in the previous section, an appropriate choice of core length enables us to minimize the isolation variation due to temperature, but one can not suppress it completely.

In order to further suppress or compensate the isolation temperature variation, we propose superimposing a bias current on the RF signal. The circuit for realizing the present compensation method is schematically illustrated in Fig. 9 in the case of a 2-way splitter which consists of one dividing and two impedance-matching transformers. In this circuit, the bias current is superimposed on the RF signal before it enters the dividing transformer’s input port. After passing through the dividing core, the DC bias flows to ground through an inductor and a resistor, while only the RF signal goes to the impedance-matching transformers. The amplitude of the bias current is adaptively adjusted according to ambient temperature so as to compensate for the isolation degradation.

![Fig. 9. Bias current superimposing system.](image)

4.2 Permeability Change by Superimposing Bias Current

In order to examine the possibility of compensating the RF 2-way splitter’s isolation variation due to temperature by means of superimposing a bias current, we conducted preliminary experiments, i.e. we measured the isolation by changing the bias current amplitude at a fixed temperature (room temperature). A measurement circuit and ferrite core parameters used in this experiment is shown in Fig. 10, where the direct bias current can be adjusted from 0 mA to 500 mA. The parameters of the ferrite core used are listed in Table 3.

![Fig. 10. Measurement circuit and ferrite core parameters.](image)

**Table 3. Parameters used in the experiment**

<table>
<thead>
<tr>
<th>Core inner diameter</th>
<th>Core outer diameter</th>
<th>Core length</th>
<th>Initial permeability</th>
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<td>0.7 mm</td>
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<td>6 mm</td>
<td>2000</td>
</tr>
</tbody>
</table>
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4.3 Measurement Results

Experimental results for the 2-way splitter’s isolations obtained with the bias current of 0 mA to 500 mA are illustrated in Fig. 11. According to the increase in the bias current, the isolation significantly improves at most frequencies above 100 MHz, though it becomes worse at frequencies lower than 100 MHz.

Fig. 11. Isolation dependence on the bias current.

5. Conclusion

The adaptive compensation method for the temperature dependence of transformer isolation, which utilizes superimposing direct current, has been proposed and the results of a preliminary experiment for that purpose have been reported. Although the experimental results in this study were obtained at a fixed temperature (room temperature), they imply that the proposed method would enable us to compensate the transformer isolation variation due to temperature by employing a bias current of an appropriate amplitude. The way of controlling the bias current appropriately is the subject of future work.

Acknowledgements

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References


Takanobu Aoyama received a B.E. degree in electrical engineering from Saitama Institute of Technology in 1983. Since 2003, he has been engaged in Tokai Polytechnic College, and is currently in the doctoral program at the Department of System Engineering at Mie University. His research interest lies in RF device design technology. He is a member of the Institute of Electronics, Information and Communication Engineers.

Yoshiki Shibata received a B.E. degree in physics engineering from Mie University in 2010, where he was engaged in research on an electromagnetic simulation of RF devices in the master’s program.
Tomohiko Kanie received a B.E. in electrical engineering from Meijo University in 1985, an M.E. in material science from the Japan Advanced Institute of Science and Technology in 1995, and a PhD degree from Mie University in 2009. He was with Sendai Polytechnic College from 1995 to 1999 and Kinki Polytechnic College from 1999 to 2001. Since 2001, he has been the CEO of Aoyama Technology Inc. and is currently in the doctoral program at the Department of System Engineering at Mie University. His major interest lies in RF passive circuit technology. He is a member of the Institute of Electronics, Information and Communication Engineers.

Yuichi Noro received B.E. and M.E. degrees from Mie University in 1984 and 1986, respectively, and a PhD in electrical and electric engineering from Nagoya Institute of Technology in 1993. Since 1986, he has been engaged in research on data analysis of acoustic noise and digital processing of acoustic signals at Mie University and is currently an associate professor. He is a member of the Acoustical Society of Japan and the Institute of Electronics, Information and Communication Engineers.

Takashi Takeo received B.E., M.E. and PhD degrees in electrical engineering from Nagoya University in 1976, 1978 and 1992, respectively. He joined the Nagoya Municipal Industrial Research Institute in 1978 and in 2005, accepted a professorship at Mie University. His chief interests lie in the application of optical and RF technology. He is a member of the Institute of Electronics, Information and Communication Engineers, the Japan Society of Applied Physics, the Laser Society of Japan, and the Society of Instrument and Control Engineers.