A New Method for Measuring the Complex Permittivity and Permeability of Sintered Material FeSiAl Used for Microwave-Absorbing Load

Fang Zhang1, Lianguan Shen1,3 and Yuanji Pei2

1 Department of Precision Machinery and Precision Instrumentation, USTC, Hefei Anhui, 230027, China
2 National Synchrotron Radiation Laboratory, USTC, Hefei Anhui, 230029, China
3 lgshen@ustc.edu.cn

Abstract. This paper describes a new method for measuring the complex permittivity and permeability of a sintered microwave-absorbing material. Thorough knowledge about microwave-absorbing materials is very important for the design and construction of accelerators. Although many methods of measuring the permittivity and permeability of a material have been developed and tested successfully, they are not suited to cases in which the microwave-absorbing material is coated on an oxygen-free high-conductivity copper (OFHC) surface by means of a special sintering technology. Thus, a new method is developed through a combination of testing and simulations. The complex permittivity and permeability of the microwave-absorbing material FeSiAl was obtained by this means, and a collinear load was designed based on the measurement results. The linear accelerator (LINAC) with the collinear load has been running well.

1. Introduction
Since the concept of RF LINACs was advanced by Ising in 1924 and tested by Wideröe in 1928, many LINACs have been built for scientific research and applications in different fields. These facilities are composed of many components, such as an accelerating structure, waveguide, RF dummy load, RF power attenuator, and high-order-mode absorber in the accelerator cavity. To control high-order modes and design a dummy load to miniaturize LINACs, a complete knowledge of microwave-absorbing materials is needed, such as their permittivity and permeability, vacuum performance, and conductivity. As for measuring the permittivity and permeability of materials in the microwave range, many academic articles have been published.1-3 It was found that these methods are not suited to cases in which the material is originally powdered and actually coated on the OFHC surface by means of high sintering in a vacuum furnace. Thus, a new measuring method in which the performance of the sample is the same as the factual was explored.

2. Principle of Measurement Method for EM Parameters
A compact electron LINAC used for a THz-source based on FEL was designed and built. To reduce the size of the LINAC, a collinear load was chosen to absorb the residual microwave power. The collinear load is a disk-loaded waveguide with many OFHC cavities and the inner surface coated by an efficient microwave-absorbing material FeSiAl. And excluding other inappropriate methods, the permittivity and permeability of the FeSiAl powder were measured in the way of the transmission and
reflection method with a coaxial line by our predecessors, who determined values of $\varepsilon=13.23-0.25i$, $\mu=1.77-1.41i$, respectively, at $f=5.712$ GHz, the working frequency in the C band.\(^4\) A collinear sample was then designed based on the values.\(^4\)

However, the measured values of the absorbing coefficient were differ from the design values by a significant amount.\(^5\) By analyzing the causes, the main reason was found to be the destruction of the coating’s layered structure where the sintered coating was ground into powder and mixed with paraffin to allow it to be molded into a hollow cylindrical specimen into the coaxial line. That is a common approach in the transmission/reflective methods to solve the problem of the gap between the sample and the wall of the line.

The FeSiAl coating was formed by a special high sintering process in a vacuum furnace by our collaborators, resulting in a multilayer material with efficient microwave-absorbing capacity. The cross-sectional structure of the coating layer is shown in figure 2. It can be seen that the sintered coating consists of three layers that are distinguished by their morphology. It has also been found that being different from other general absorbing materials, the coating layer benefits from both its chemical components and its microstructure.\(^6\)

![Figure 1. Section structure of the FeSiAl coating observed under a scanning electron microscope.](image)

The different layers play their respective roles to ensure that the whole FeSiAl coating offers efficient microwave-absorbing capacity, good thermal conductivity, and machinability. And this leads to the conclusion that the structure as well as the performance will change from the powdery after sintering. Therefore, the measurement process should ensure that the original structure of the FeSiAl coating is retained while obtaining the accurate electromagnetism parameters of the sample.

### 3. Sample Design and EM Parameters Solution

Based on the above measuring principle, a new structure for the test samples was designed at $f = 5.712$ GHz, as shown in figure 2. This is basically a wedge-shaped section of standard rectangular waveguide ($a \times b$) that has been terminated with an inclined short-circuit plate coated with FeSiAl. Compared with the circular waveguide, the plane surface of the rectangular can simplify the coating process while ensuring the uniformity and consistency of the properties of the coating material. Due to the increase of the intensity of electromagnetic field with the transverse area decrease, an inclined form of the coating plate can effectively increase the attenuation of the sample. This can not only get enough attenuations in smaller size but also save the material. In this case, adjusting the slope of the plate gives a series of geometries to satisfy the demands of measuring different attenuation coefficients without additional processing of the sintering molded coating.
In accordance with the transmission/reflection techniques, the attenuation performance $\alpha_L$ of the sample load is directly related to the complex permittivity and permeability of the coating material once the structure is determined. This can be described as follow

$$\alpha_L = f\left(\varepsilon, \varepsilon', \mu, \mu'\right)$$

(1)

To acquire the EM parameters $\varepsilon$ and $\mu$, the relationship $f^{-1}(\alpha_L)$ in equation (1) should be solved. For odd-shaped objects as the sample with stepped cross-sections, the EM field is too complicated to do that. In our situation, a method combining experimental measurements with numerical simulations was proposed. CST Microwave Studio is a specialized tool for 3D EM simulations of high-frequency signals based on finite integration. The attenuation of the loads shown in figure 2 can be solved by CST with the given EM parameters of the coating. Thus, data can be obtained to represent the mapping in equation (1) between the EM parameters and the attenuation of a known structure.

By using the common polynomial approximation approach, the regression model between the two can be written in the polynomial form as follow

$$\alpha_L = \sum c_i (\varepsilon^*)^m (\mu^*)^n$$

(2)

Generally, determining four unknowns requires four equations, i.e., at least four different geometries (the combinations of Length and Thickness shown in figure 2 are chosen). For the four equations, the mapping between the attenuations and the EM parameters of the absorbing material can be expressed in matrix form, which can be simplified to

$$[\alpha_L] = [C][EM]$$

(3)

With the help of CST, the attenuations of the measured samples for different EM parameter values of the absorbing material were simulated to form the functional projective relationship. By this means, the coefficient matrix $[C]$ was obtained from the simulated data, allowing the EM parameters to be calculated from the measured attenuations $\alpha_L$.

4. Test Devices and Measurement Results

Using the improved method, four test samples working in the C-band were prepared based on the previous measured values. The experimental device for the measurements is shown in figure 3. The device consists of a vector network analyzer, a coaxial-to-waveguide adapter, and the section being measured.
The measurement results for the four samples are presented in table 1, which includes the corresponding design attenuations and structure parameters.

| No. | Structure Length/mm | Thickness/mm | VSWR Design | VSWR Measure |
|-----|---------------------|--------------|-------------|--------------|
| 1   | 40.0                | 0.10         | 15.81       | 12.84        |
| 2   | 40.0                | 0.20         | 11.63       | 9.48         |
| 3   | 56.5                | 0.10         | 10.52       | 9.12         |
| 4   | 56.5                | 0.20         | 6.75        | 5.44         |

The results show that the attenuation performance of the material is better than the previous measured value. The coefficient matrix \([C]\) was then determined by means of the least-squares method with groups of random numbers and the simulated attenuations.

Actually, in consideration of the different effect of the four values on the attenuation, the matrix formula in equation (3) may be written as follow

$$[EM] = [T][\alpha_L]$$

(4)

The \(\alpha_L\) is regarded as the input while the EM parameters become the output of the response system. This can not only simplify the arithmetic, but also improve the precision of the secondary factors. Therefore, the EM parameters of the FeSiAl coating can be obtained from the measured results in table 1 when the matrix \([T]\) has been established in the same way.

The order of the fitting polynomial in equation (2) and (4) is also selected by comparing the given and response values of the EM parameters. The comparison results show that an order-five polynomial is enough to ensure a residual error of less than 6% in parts of the EM parameters. This means the calculated coefficient matrix \([T]\) can determine the relation between the EM parameters and the attenuation of the measured samples.

Based on the measured data presented in table 1, the relative permittivity and permeability of the FeSiAl coating can be calculated as \(\varepsilon = 113.09-10.92i, \mu = 0.49-1.07i\) \((f = 5.712 \text{ GHz})\) with matrix \([T]\).

5. Verification of the Measurement Method

To further verify the reliability and accuracy of the proposed method, a welded sample with FeSiAl coated was designed and manufactured. The comparison as shown in figure 4 indicates that there is good consistency between the results. This demonstrates the validity of the proposed method.
Further, to satisfy the demands of a THz-source, a collinear load composed of four cavities has been simulated and manufactured based on the measured EM parameters. The measurement results of the cavities showed that the deviation of the resonant frequency of each cavity to the working frequency is less than 150 kHz while the one-way attenuation of the load is 17 dB, satisfied the design requirement. Actual running of the LINAC also showed that the collinear load works well.

6. Summary and Conclusion

To understand the complex EM parameters of sintered microwave-absorbing FeSiAl, a new method combining testing and simulations has been proposed. A new measuring structure was designed to ensure that the original and unique structure of the coating is retained while obtaining the electromagnetism parameters. Based on the electromagnetism theory, a matrix equation was deduced to establish the relationship between the measured attenuation coefficient of the structure and the EM parameters of the absorbing material. And the complex permittivity and permeability of FeSiAl at 5.712 GHz were found to be $\varepsilon=113.09-10.92i$, $\mu=0.49-1.07i$ by this means. A comparison between simulated and experimental results shows that the proposed method is reliable. The measurement method is considered to be effective for similar sintered materials in the microwave band.

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