Application of Microwaves and Millimeter Waves for the Characterization of Teeth for Dental Diagnosis and Treatment

Naoya Hoshi, Yoshio Nikawa, *Member, IEEE,* Keiji Kawai, and Shigeyuki Ebisu

***Abstract*—This paper presents applications of microwaves and millimeter waves for the characterization of teeth. This is done by measuring the complex permittivity over the frequency range from 0.04 to 40 GHz. These measurements have revealed that dental caries are significantly more lossy to microwaves and millimeter waves than the healthy tooth, and this difference can be used for dental diagnosis. The experimental results have been confirmed by using the finite-difference time-domain (FDTD) method. In addition, millimeter-wave heating of the lossy dental caries can be used as a sterilization treatment. It is concluded that millimeter waves can be used for dental medical diagnosis as well as dental medical treatment.**

***Index Terms*—Dentistry, FDTD methods, measurement, medical diagnosis, permittivity, scattering parameters measurement.**

I. Introduction

Conventional diagnosis of dental caries has been conducted by a dentist's subjective judgment based on observation of change of color, odor, surface hardness, and clinical symptoms such as pain. X-ray imaging provides a more objective diagnosis, but this technique can cause biological damage to human tissues. With X-ray diagnostic methods, the initial stage of dental caries cannot be differentiated easily from the healthy tissues. The dental caries are then treated using a high-speed rotary cutting apparatus. Decayed tissues, which are usually softened and infected, are removed. Healthy tissues surrounding the decayed tissues are also removed during this treatment. Because of this, a more nondestructive diagnosis and treatment procedure is highly desired.

In the past, microwaves and millimeter waves have been applied to various medical treatments. However, there seems to be no sufficient reports presenting the applicability of microwaves and millimeter waves to the field of dental medical treatment. In this paper, the possibility of using microwaves and millimeter waves for dental diagnosis has been investigated by measuring the complex permittivity of enamel, dentin, and dental caries. These results suggest that dental caries diagnosis using millimeter waves can be based on differences in loss between dental caries and the healthy tooth. Experimental measurements of transmission coefficients have been conducted and confirmed by the finite-difference time-domain (FDTD) analysis [1], [2] to demonstrate a potential clinical procedure.

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N. Hoshi and Y. Nikawa are with the Department of Communication Engineering, School of Electrical Engineering, National Defense Academy, Yokosuka, 239-8686 Japan.

K. Kawai and S. Ebisu are with the Department of Conservative Dentistry, Osaka University, Osaka 565-0871, Japan.

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II. Complex Permittivity

The reflection coefficient for various samples was measured using a Wiltron 360B Vector Network Analyzer along with an open-ended coaxial probe attached directly to the samples. The network analyzer had been calibrated at the end of the coaxial probe using open and short standard and terminations. The complex permittivities of samples were obtained by making a comparative calculation between samples and a standard material [3]–[5]. The open-ended coaxial probe was used to interface the measuring equipment with the samples in all cases.

Samples of adult's teeth were extracted. The tooth material was classified as enamel, dentin, and dental caries. The complex permittivities of enamel and dentin were taken as the average of 10 measurements, respectively. Some dental caries are composed of soft and watery tissues. The moisture content in dental caries changes as the condition of caries changes. In order to know the dental caries' condition, they were classified by their moisture content as a function of time after being removed from a preservative solution. The moisture content will decrease as a function of time after removal from the preservative solution.

Fig. 1 shows the average value of complex permittivity of enamel and dentin calculated from the reflection coefficient. It was found that the values for enamel and dentin were different. A tooth is composed of an organic and inorganic constituent with some moisture content. The complex permittivity is most strongly influenced by the moisture content. Table I shows the composition of enamel and dentin [6].

Fig. 2 shows the complex permittivity of dental caries. Type 1 denotes the highest moisture content, followed by types 2 and 3 with lower moisture content, respectively. As shown in Fig. 2, the greater the moisture content, the higher the permittivity.

As shown in Fig. 3, the dental caries' loss tangent decreases as the moisture content decreases.

III. Basic Concept of Tooth Diagnosis

The loss tangent of dental caries is significantly higher than for a healthy tooth. Dental caries are soft and have a high

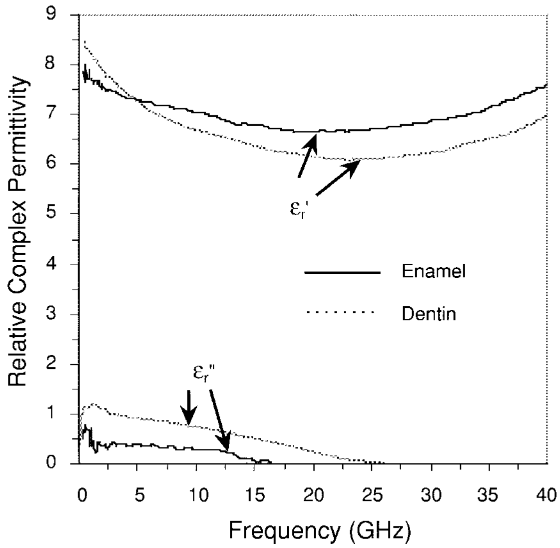

Fig. 1. Relative complex permittivity of enamel and dentin.

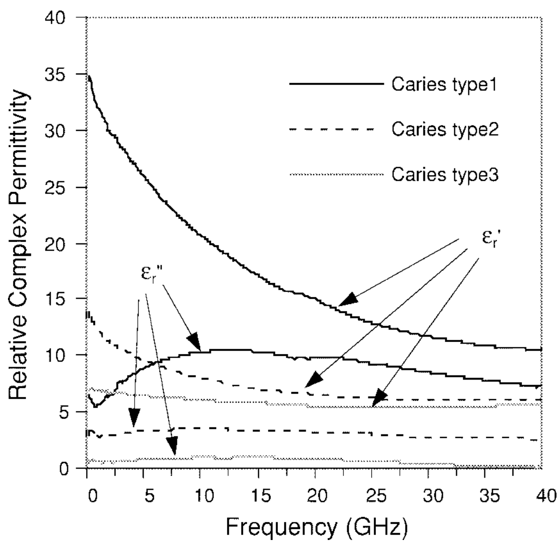

Fig. 2. Relative complex permittivity of caries.

TABLE I
COMPOSITION OF ENAMEL AND DENTIN

	Inorganic constituent	Organic constituent	Moisture content
Enamel	97.2 wt%	0.3 wt%	2.5 wt%
Dentin	65 wt%	20 wt%	15 wt%

moisture content resulting in a high loss tangent. Based on these results, it is predicted that millimeter-wave transmission measurements would be different between a healthy tooth and dental caries.

IV. Theoretical Consideration

A. FDTD Simulation

A three-dimensional electromagnetic-field analysis of the tooth was made using FDTD at 35 GHz. The FDTD method

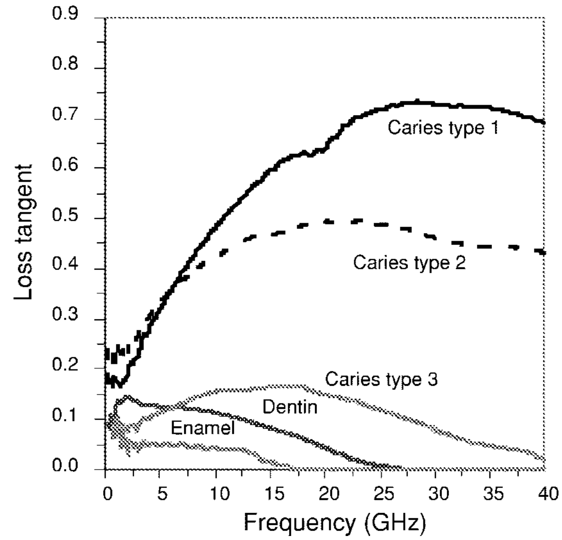

Fig. 3. Loss tangent of tooth.

TABLE II
CELL SIZE OF EACH MEDIUM

	δx (mm)	δy (mm)	δz (mm)
Waveguide and free space		0.72192	
Silicone rubber	0.35	0.5	0.35
Tooth and dental caries		0.218499	

was chosen because of its flexibility and efficiency in solving complex heterogeneous geometries. The simulation was made at 35 GHz because the wavelength was small enough, relative to the tooth size, to provide a large differentiation between dental caries and healthy tooth components, and because the applicator can be small. In order to simplify the computations, the boundary conditions were solved over a smaller area [7]. The size of the calculated region was 30 $\times$ 46 $\times$ 20 cells. The time step δt of the FDTD calculation was 0.2 ps. In order to converge to a solution, the cell size was varied for each medium. Table II shows the cell size of each medium. As shown in Fig. 4, two models were used: model A for a healthy tooth and model B, which contains dental caries. In model A, the dentin and enamel thickness is 2.18 mm. In model B, the tooth and dental caries are each 1.09-mm-thick. The piece of silicone rubber that was used as part of the actual measurement was 1.5-mm-thick. The aperture size for the waveguide was 3.5 $\times$ 7.0 mm. The waveguide length was 10.83 mm. The generated source electromagnetic wave is expressed by

$$E_z = \sin\left(\frac{\pi x}{a}\right)\sin(2\pi f n \delta t) \tag{1}$$

where n is reiteration times, a is width size of waveguide aperture (7 mm), and f is frequency (35 GHz). The relative complex permittivities used for each medium are shown in Table III. In Table III, the relative complex permittivity of the healthy tooth is the average of enamel and dentin, and the

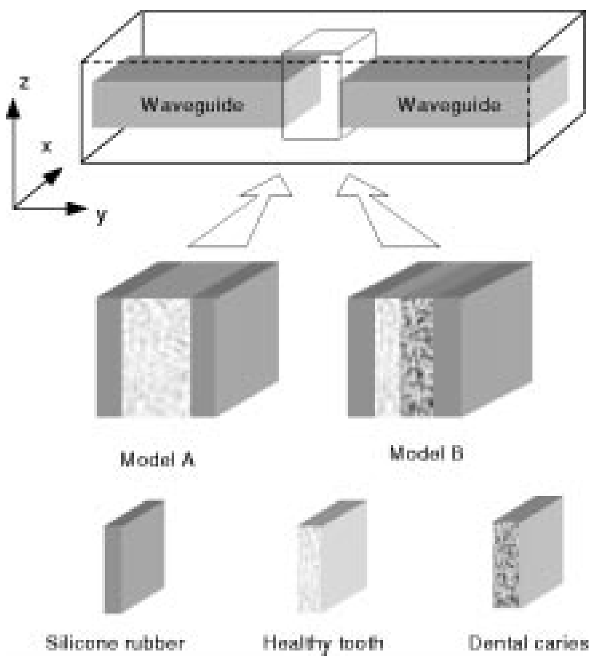

Fig. 4. Analysis model.

TABLE III
RELATIVE COMPLEX PERMITTIVITY OF EACH MEDIUM

	ε_r'	ε_r''
Healthy tooth	6.83	0.02
Dental caries	6.04	2.64
Silicone rubber	2.7	0.01

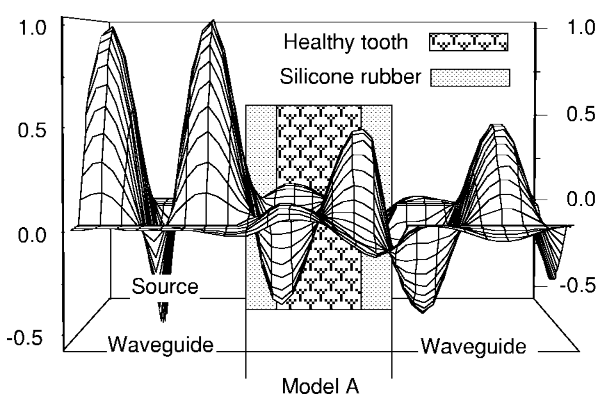

Fig. 5. Electric-field distribution in healthy tooth.

relative complex permittivity of the dental caries is the value of caries for type 2, as shown in Fig. 2.

B. Simulation Results

Figs. 5 and 6 show the electric-field distribution in the healthy tooth and in the tooth with dental caries. The wave penetrates each medium at the receiving waveguide. It is observed that the amplitude of transmitted waves through the dental caries is lower than that through the healthy tooth because of the greater loss tangent of the dental caries.

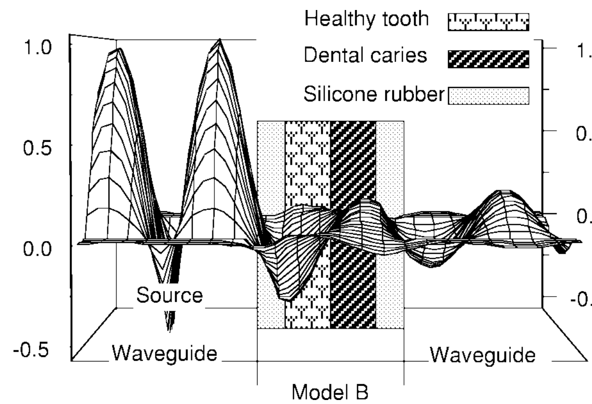

Fig. 6. Electric-field distribution in tooth including caries.

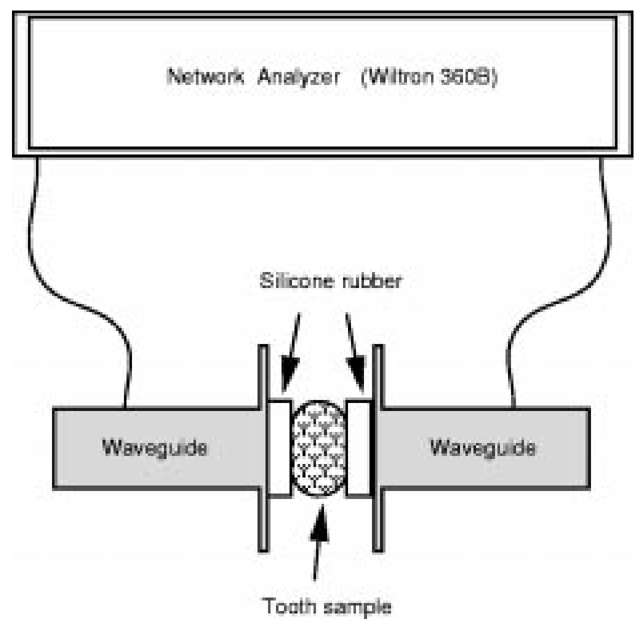

Fig. 7. Experimental system.

V. EXPERIMENT

A. Measurement

In order to compare the simulated and measured results, the transmission coefficient for the tooth was measured at 35 GHz. As shown in Fig. 7, a sample tooth is irradiated by the millimeter waves using a rectangular waveguide. The transmitted wave was received by a waveguide located on the opposite side of the sample. The transmission coefficient (S_{21}) was measured by a network analyzer. In order to reduce the effect of the mismatch of the air gap between the probe and the sample, silicone rubber sheets were placed in the apertures of both waveguides. The aperture size of the waveguide is 3.5 mm $\times$ 7.0 mm. Five samples were measured. Extracted adult's teeth were used for the samples. As shown in Fig. 8, samples 2–5 consist of two parts, one containing dental caries and the other part containing only healthy tooth. Sample 1,

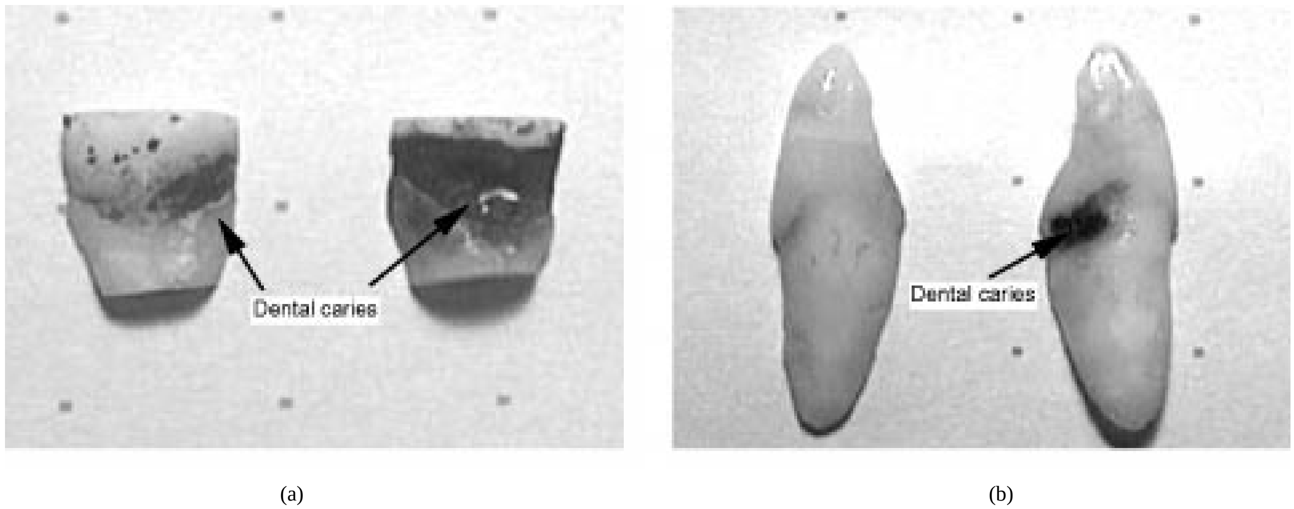

Fig. 8. Photo of tooth. (a) Sample 1. (b) Sample 2.

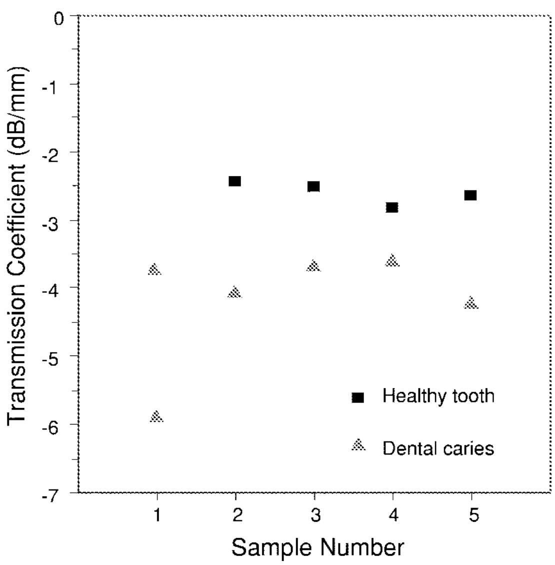

Fig. 9. Transmission coefficient of millimeter waves (35 GHz).

which had severe dental caries, was divided into a heavy caries part and a light caries part.

B. Experimental Results

To evaluate and compare the data, the transmission coefficients [decibels/millimeters] were obtained, and are shown in Fig. 9. For samples 2–5, it is shown that the value for dental caries is about 1 dB lower than that for a healthy tooth. In sample 1, the value for dental caries is about 3 dB lower than that for the healthy tooth. This result indicates that the transmission coefficient of dental caries is lower than that of a healthy tooth and varies strongly with the degree of caries. The transmission coefficients of the healthy tooth are very uniform, as shown with samples 2–5. However, the sizes of the dental caries were small in comparison with the aperture size for the waveguide. By using a smaller aperture, it should be possible to locate the dental caries more precisely within the tooth by measuring a greater deviation in transmission coefficient.

TABLE IV
COMPARATIVE STUDY OF THEORY AND EXPERIMENT

	Transmission coefficient (dB / mm)			
	Theoretical data	Experimental data		
		mean	max.	min.
Healthy tooth	-2.43	-2.63	-2.83	-2.44
Caries (type 2)	-6.12			
Caries (average of types 2 and 3)	-4.65	-4.32	-5.9	-3.61
Caries (type 3)	-3.03			

TABLE V
RELATIVE COMPLEX PERMITTIVITY OF EACH MEDIUM

	ε_r'	ε_r''
Healthy tooth	6.83	0.02
Caries (type 2)	6.04	2.64
Caries (average of types 2 and 3)	5.79	1.47
Caries (type 3)	5.53	0.3

In Table IV, theoretical and experimental results are compared. The theoretical values of transmission coefficient were obtained by using the FDTD method. For the healthy tooth, the values are similar. For samples with dental caries, the values vary widely in experimental data depending on the dental caries condition. However, by incorporating the values in Fig. 2 into the FDTD models, theoretical data indicates similar values for maximum, minimum, and mean values, as with the experimental data. The incorporated relative complex permittivities are shown in Table V. In this table, the value for the healthy tooth is the average of enamel and dentin. The values for dental caries are the values of caries types 2 and 3 and the average of types 2 and 3 in Fig. 2, respectively.

VI. Consideration of Tooth Treatment

The attenuation of the millimeter waves by the dental caries suggests that the caries can be heated in order to kill the microorganisms, including bacteria and virus in the caries by dielectric heating. It has been reported that some portion of the dental caries can become calcified on the condition that the caries are kept aseptic [8]. Since dental pulp is made of fairly sensitive tissues and because the region of dental caries is very small, it is important to focus the millimeter waves on the caries. High power levels and small applicator size is necessary to selectively kill the microorganisms in the dental caries.

VII. Conclusions

The loss tangent of dental caries is shown to be significantly higher than that of a healthy tooth. Therefore, the transmission coefficient of dental caries is lower than that of a healthy tooth. This difference has been confirmed by measurement and FDTD simulations. This result can be applied to dental caries diagnosis.

In addition, the results of this paper demonstrate the potential to apply millimeter-waves absorption as a nondestructive diagnosis and treatment technique for dental caries. Further research is needed to determine the differences in absorption between teeth *in vitro* and *in vivo.*

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Naoya Hoshi was born in Fukushima, Japan, on August 30, 1968. He received the B.S. degree in electrical engineering from the National Defense Academy of Japan, Yokosuka, Japan, in 1992, and is working toward M.S. degree.

His current research interests are microwave applications for medical field and microwave measurements.

Yoshio Nikawa (M'88) was born in Tokyo, Japan, in 1958. He received the B.E., M.E., and Ph.D. degrees in electrical engineering from Keio University, Yokohama, Japan, in 1981, 1983, and 1986, respectively.

From 1986 to 1987, he was a Research Assistant at the National Defense Academy. From 1987 to 1988, he was a Research Associate at the University of Texas at Austin. He is currently an Associate Professor of electrical engineering at the National Defense Academy, Yokosuka, Japan. His current research interests include microwave measurements and applications and electromagnetic-wave heating technique for medical and industrial applications.

Dr. Nikawa is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE), Japan, the Japan Society of Medical Electronics and Biological Engineering, and the Japanese Society of Hyperthermic Oncology.

Keiji Kawai was born in Nagoya, Japan, on July 14, 1957. He received the D.D.S. and Ph.D. degrees in dentistry from Osaka University, Osaka, Japan, in 1984 and 1988, respectively.

From 1988 to 1989, he was a Research Assistant at Osaka University. From 1991 to 1992, he was a Visiting Assistant Professor at the University of Alabama at Birmingham. Since 1989, he has been an Assistant Professor at Osaka University, Faculty of Dentistry. His current research interests include diagnosis of dental caries and treatments by various kinds of dental materials and devices.

Dr. Kawai is a member of the Japanese Society of Conservative Dentistry and the Japanese Society for Dental Materials and Devices.

Shigeyuki Ebisu was born in Osaka, Japan, on March 14, 1948. He received the D.D.S. and Ph.D. degrees from Osaka University, School of Dentistry, Osaka, Japan, in 1972 and 1976, respectively.

From 1976 to 1978, he was a Research Associate at the Medical School, University of Michigan at Ann Arbor. From 1990 to 1996, he was a Professor at the School of Dentistry, Tokushima University, Tokushima, Japan. Since 1997, he has been a Professor at Osaka University, Faculty of Dentistry.

Dr. Ebisu is a member of the Japanese Society of Conservative Dentistry and the Japanese Society of Periodontology.