Experimental Study of Microwave Transmission in Snowpack

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Abstract—**Microwave transmission loss in a natural snowpack was measured to provide fundamental data for snow subsurface radar. The snowpack consisted of many horizontal stratified layers of relatively large density and water inclusion. Field strength measurements were carried out in the vertical direction across horizontal snow layers. The transmission loss and the extinction coefficients were obtained as a function of frequency.**

I. INTRODUCTION

THE field of microwave remote sensing has seen a recent growth in snow radar. The microwave FM-CW under-snow radar [1], [2] and the microwave holographic radar [3] that detects buried objects within a snowpack has been particularly promising. If the snow region applications of remote sensing become practical, they will provide a powerful tool to search, for example, for buried metallic objects which might obstruct a snow rotary machine or, in an emergency situation, to rescue men trapped in an avalanche, etc. Our goal is to develop a real-time under-snow FM-CW radar operative in an actual snowpack. It is necessary to investigate how microwaves propagate in real snowpacks, and to select the optimum frequency spectrum for the radar.

Snowpacks, in general, consist of many different snow layers with varying electrical properties. The upper portion of the snowpack undergoes melting and refreezing continuously, and is covered and pressed against by newly fallen snow. Hence, a given snow layer and its corresponding dielectric properties change with time and season. Dielectric properties of snow have been reported at microwave frequencies [4]–[8]. However, it is necessary to investigate how the field strength changes within a real snowpack consisting of many different snow layers in order to fine tune the radar to practical use. The device is expected to be used in very adverse conditions; i.e., in very highly dense and wet snow conditions. To the authors' knowledge, there is no report treating microwave transmission in such real wet snowpacks. This paper presents the basic properties of microwave propagation in real snowpacks. The snowpack's field strength measurements were carried out at a frequency range of 0.6–7 GHz.

II. EXPERIMENTAL ARRANGEMENT

Fig. 1 shows a block diagram of the arrangement used to measure microwave transmission loss within a snowpack. A sweep oscillator (maximum output power: 100 mW) is used as a signal source, emitting a swept frequency signal with a period of 10 ms. The bandwidth of a swept signal is determined by the operative band of a transmitting horn antenna. We divided the entire frequency band of 0.6–7 GHz into five bands; i.e., 0.6–1.2 GHz, 1.2–2.2 GHz, 2.2–4.4 GHz, 4–6 GHz, and 5–7 GHz. The swept frequency signal, which has a continuous frequency spectrum, is sent into the snowpack through a rectangular horn antenna. The field strength inside the snowpack is picked up by a small dipole which moves along a very small opening in the vertical direction. The receiver arrangement consists of a spectrum analyzer, an analog-to-digital converter, a microcomputer system, and an antenna driving unit. The latter is an antenna positioner whose stepping motor is controlled by the microcomputer with a precision error of 8/1000 mm. The measuring interval between adjacent points can be adjusted arbitrarily in the range from 1 to 5 cm, depending on snow conditions. At one point along a small vertical opening in a snowpack, a swept signal is picked up by the spectrum analyzer, and the continuous spectrum output is converted into digital signals and is recorded onto a floppy disk. Once the data at the point are recorded, then the receiving dipole moves to the next point, and the receiving instrument repeats the same procedure until the receiving dipole reaches the final point. In this manner, field intensities in a snowpack are obtained.

In this measurement, there arise two types of waves that propagate in the snow. The first one propagates through the snow medium itself. The other one propagates through the small hole that has to be drilled for the small dipole antenna to move along. However, the effect of the latter wave is negligible because the hole is small enough that the wave propagates in the cutoff frequency region; i.e., it attenuates very rapidly. The detailed quantitative com-

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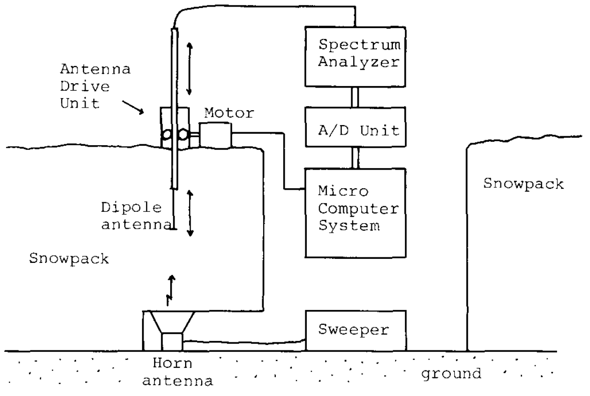
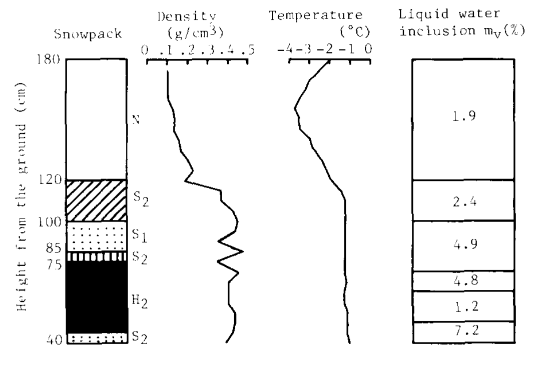


Fig. 1. Block diagram of transmission system.



Snow Type : N - New snow, S_1 - Grained snow
S_2 - Fine grained snow
H_1 - Fine depth hoar, H_2 - Depth hoar

Fig. 2. Snowpack under measurement on February 8, 1988 (Case A).

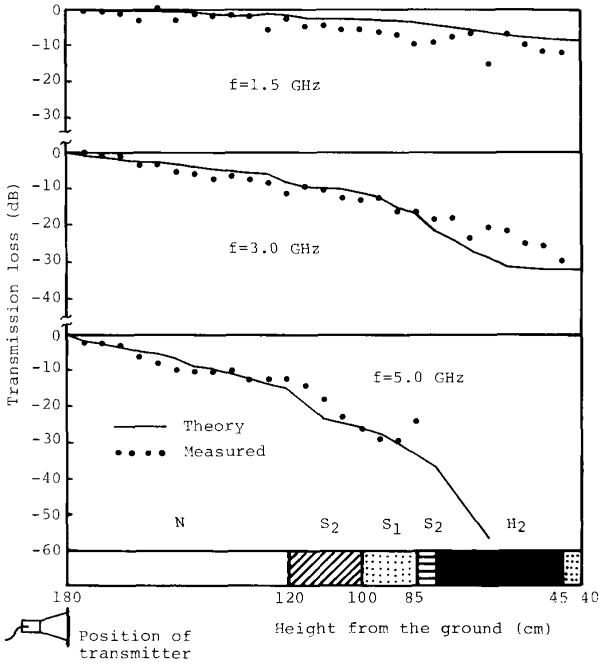


Fig. 3. Microwave transmission loss in snowpack (Case A).

parison is given in the Appendix. Thus the transmission and the attenuation characteristics of the microwave are due to the snow medium in this measurement.

III. FIELD EXPERIMENTS

Niigata, Japan is a very heavy snowfall region, with snowpacks piling up to as high as 2-4 m every winter. We measured the propagation characteristics within several kinds of snowpacks at various locations; i.e., snowpacks consisting of new snow and/or old snow.

A. Case A

An experiment was carried out on February 8, 1988 at Yunotani Village, Niigata, Japan. The snowpack depth was 1.8 m. Prior to the transmission experiment, we measured the temperature, density, and wetness of each layer of the snowpack. The upper portion of the snowpack was new snow with a wetness of 1.9%. These physical values are plotted in Fig. 2, together with the snow type.

The nomenclature of snow type is due to [8], [9], and is defined as follows;

N: new snow, S_1: grained snow, S_2: fine grained snow, H_1: fine depth hoar, H_2: depth hoar.

Some examples of the measured transmission loss along the vertical direction across each layer are shown in Fig. 3, with theoretical values based on the well-known transmission line theory [10]-[13]. These values are normalized at the top position, and the measuring interval is 5 cm. In this experiment, the transmitting antenna was set at the top surface of the snowpack. From Fig. 3, it is seen that the transmission loss strongly depends on frequency.

In the theoretical calculation, we regarded the snowpack as a multiple stratified medium consisting of many homogeneous layers in the horizontal direction. This simple modification enables us to apply the transmission line theory [13]. Since the transmission line theory is well known, we omit the formulation here. The detailed formulation and expressions are given in [13].

In order to determine the transmission loss at an arbitrary point in the snowpack, it is necessary to determine the dielectric constant of each layer. According to the results [5], the dielectric constant of each snow layer is determined using the snow wetness m_v and dry snow density ρ_{ds}, based on the semi-empirical Debye-like model [5], [6]. The snow wetness m_v is the liquid water inclusion in volume, i.e., the volume fraction of liquid water measured by percentage. The relative dielectric constant of wet snow $\epsilon_{ws} = \epsilon'_{ws} - j\epsilon''_{ws}$ is given by

$$\epsilon'_{ws} = A + \frac{B m_v^x}{1 + (f/f_0)^2} \quad (1)$$

$$\epsilon''_{ws} = \frac{C (f/f_0) m_v^x}{1 + (f/f_0)^2} \quad (2)$$

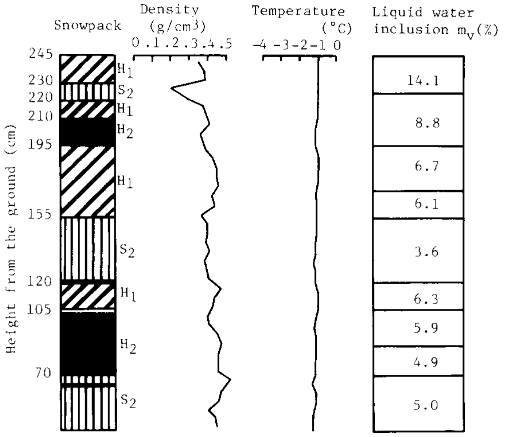


Fig. 4. Snowpack under measurement on March 12, 1988 (Case B).

$$A = 1.0 + 1.83 * \rho_{ds} + 0.02 * m_v^{1.015} \quad (3)$$

$$B = C = 0.073, \quad f_0 = 9.07, \quad x = 1.31 \quad (4)$$

where f_0 is the relaxation frequency and f is the operating frequency, both measured in gigahertz. A, B, C, and x are all constants. The details have been given in [5]. It should be noted here that the dielectric behavior of wet snow is determined mainly by water inclusion.

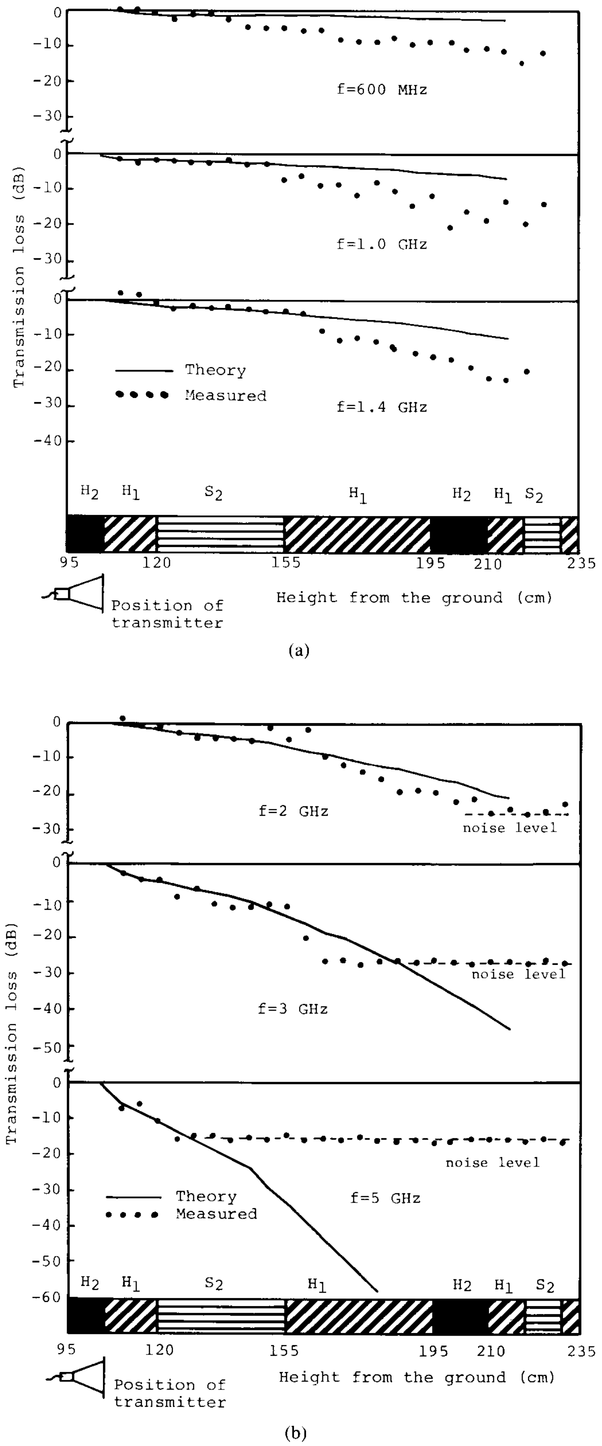
As seen in Fig. 3, the transmission loss is in close agreement with the measured data. This is mainly due to the snow type, i.e., the new homogeneous snow layer with relatively small water inclusion.

B. Case B

Fig. 4 shows the other snowpack (depth: 2.45 m on March 12, 1988). The snowpack had repeatedly undergone melting, rainfall, and refreezing, and had a high degree of wetness and a temperature of −1°C throughout.

Examples of microwave transmission inside the snowpack are shown in Fig. 5, together with the theoretical curve [13]. In the calculation, the dielectric constant was derived based on the snow wetness of each snow layer. In this experiment, the snowpack was very wet. Hence, the microwave reflection at the air–snow interface was large because of impedance discontinuity. Thus, only a fraction of the energy was transmitted into the snowpack. In addition, the attenuation of the field strength in the snowpack was large. Hence, the dynamic range of the transmission measurement became relatively narrow at high frequencies above 2 GHz. The noise level of the receiver is also depicted in this figure. We tried all possible means to make impedance matching at the air–snow interface at hand, but they resulted in no improvement for this heavily wet snow.

As can be seen in Fig. 5, there are differences between measured data and theoretical values, namely, the measured transmission loss is large compared to the theoretical value, especially at the interval between 155–220 cm. This seems to be caused by heavy water inclusion in the snowpack and inhomogeneity within the snowpack. In addition, the equation for the dielectric constant is not as accurate for frequencies below 3 GHz.



(a)

(b)

Fig. 5. Microwave transmission loss in snowpack (Case B).

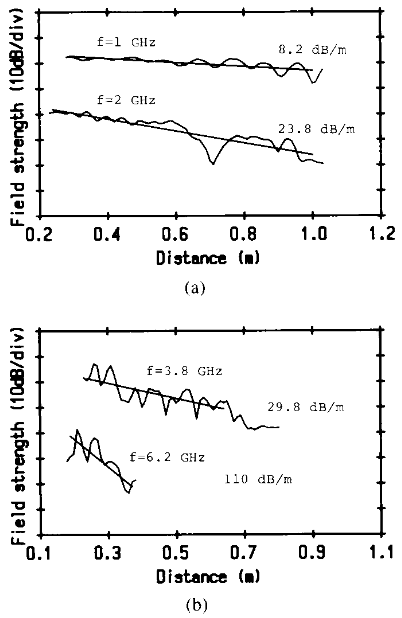
IV. Extinction Coefficient

In a real situation in which subsurface radar would be needed, the snowpack would have undergone melting and refreezing many times, and would have been mixed by external forces (i.e., an avalanche). Hence, the snow boundaries of each layer would not be clearly defined. Accordingly, we mixed several types of snow (new snow, wet snow, and old refrozen snow) thoroughly with a snow rotary machine. This almost homogeneous mass was then piled to a height of 178 cm. The density was 0.4 g/cm^3 and the snow wetness was about 5%. The transmission measurement within this artificially piled snowpack was carried out on January 16, 1987.

Some examples of the received field strength in this artificially piled snowpack are shown in Fig. 6. The horizontal axis in Fig. 6 represents the distance between a transmitting horn and a receiving dipole. Two measured curves are drawn together in this figure to show frequency characteristics. These values are relative. As can be seen, the field strength decreases somewhat oscillatorily with increasing distance and fades away rapidly with increasing frequency. The straight lines in these figures are regression lines determined by the least squares method, indicating the extinction coefficient (attenuation constant). The fluctuation of the field strength seems to be caused by some inhomogeneities within the snowpack, whose scale is larger than the wavelength in the snowpack.

In the frequency range below 10 GHz, the snow particle size is much less than the wavelength. Hence, the scattering loss by the snow particle in the snowpack may be neglected [6] compared to the absorption loss. The quantitative comparison is given in the Appendix. The extinction coefficient (scattering plus absorption) is equal to the attenuation constant of the medium as long as it is homogeneous. Accordingly, we assumed the whole snowpack as a homogeneous lossy medium, and we calculated the theoretical extinction coefficients of the snowpack at different frequencies (Fig. 8). The theoretical expression for the extinction coefficient is given in the Appendix. This extinction coefficient is determined by the relative dielectric constants of the snowpack, based on the measured water inclusion and density. The theoretical extinction is very sensitive to the variation of water inclusion and is less sensitive to density.

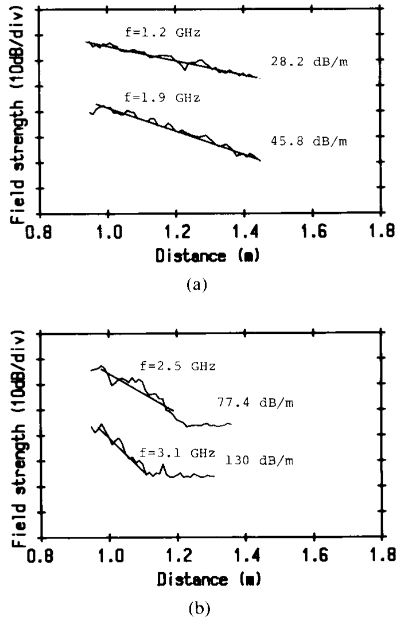
We also measured the field strength in a snowpack in natural conditions, namely, at Mount Tateyama, located in Toyama Prefecture, on April 23, 1986 (Fig. 7). The snow density was 0.5 g/cm^3, and the wetness was 5% at the upper position of the snowpack and 14% at the bottom. The fluctuation in this natural snowpack is small compared to that in the artificially piled snowpack (Fig. 6). The extinction result of this very wet snow is shown in Fig. 8.



(a)

(b)

Fig. 6. Examples of received field strength in natural snowpack on April 23, 1986.



(a)

(b)

Fig. 7. Examples of received field strength in natural snowpack on April 23, 1986.

From Fig. 8, the theoretical extinction coefficient is in agreement with the measured value at frequencies about 2 GHz for an almost homogeneous snowpack. The measured extinction coefficient is larger than the predicted values at frequencies below 2 GHz. This seems to be caused by a near-field measurement.

V. Discussion

We simplified the theoretical treatment of the microwave propagation characteristics by regarding the snowpack medium as a multi-layered structure. Admittedly,

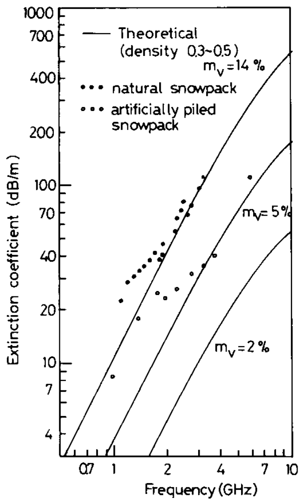


Fig. 8. Frequency characteristics of the extinction coefficient for an almost homogeneous snowpack.

this modification seems to be justified only when the snowpack consists of horizontally uniform snow layers with low water inclusion. In general, snow has two distinct regimes of liquid saturation [7]. In the lower range, called the pendular regime, the water inclusion is about 0–2%, and in the higher range, called the funicular regime, the water inclusion is over 3% and up to 14%. There is a sharp transition between the two regimes. If a snowpack consists of much thin wet snow layer in the funicular regime, which implies a high variability in electrical properties, it is very difficult to determine microwave transmission in the snowpack. Therefore, it is necessary to acquire many data in the future.

From the standpoint of radar resolution, it is recommended to use as high a frequency as possible. On the other hand, the experimental result indicates that the extinction in the wet snowpack strongly depends on the snow conditions and increases rapidly for frequencies above 2 GHz. The lower frequencies can penetrate deeper into the snowpack; however, a large impractical antenna must be used, and the resolution is reduced. Consequently, it seems appropriate to use frequencies between about 1 and 2 GHz to detect buried objects in wet snowpacks.

VI. CONCLUSION

It is very difficult to determine the microwave transmission characteristics inside snowpacks of changing electrical properties with time and inhomogeneities. Snowpacks do not necessarily consist of uniform horizontal layers. Rather, their structure is highly irregular. Hence snowpacks may be considered three-dimensional inhomogeneous media.

From the experimental results as well as from considerations on antenna size and radar resolution, a frequency range of about 1–2 GHz seems to be a suitable spectrum for remote sensing in snowpacks with high water inclusion and density, although the extinction and/or attenuation characteristics depend on the specific type of snow; i.e., density, temperature, water inclusion, etc.

APPENDIX
THEORETICAL CONSIDERATION OF EXTINCTION COEFFICIENT IN SNOWPACK

In this appendix, we examine the theoretical extinction coefficient in the snow medium.

First, we compare the scattering loss and the absorption loss due to snow particles. If the snow particle size is much smaller than the wavelength, the well-known Rayleigh approximations apply for the scattering and the absorption efficiency [6]. We roughly estimate these two contributions. Assuming the snow particle as a dielectric sphere of radius r and assuming that it is much smaller than the wavelength λ, which corresponds to our measurement, the following condition holds:

$$|n\chi| \ll 1 \qquad \text{(A1)}$$

where n is the complex refractive index of the particle to the background medium and $x = 2\pi r/\lambda$. Under this condition, the Mie expressions for the scattering efficiency ξ_s and absorption efficiency ξ_a are written as follows [6, vol. 1, p. 295]:

$$\xi_s = 8/3\,\chi^4\,|K|^2 \qquad \text{(A2)}$$

$$\xi_a = 4\,\chi\,\mathrm{Im}(-K) \qquad \text{(A3)}$$

where Im means "the imaginary part of" and K is a complex quantity defined in terms of the complex index of refraction n:

$$K = \frac{n^2 - 1}{n^2 + 2} = \frac{\epsilon_{ws} - 1}{\epsilon_{ws} + 2}. \qquad \text{(A4)}$$

Here, $\epsilon_{ws} = \epsilon'_{ws} - j\epsilon''_{ws} = n^2$ is the relative complex dielectric constant.

Fig. 9 compares the scattering and absorbing efficiency, in which the radius r of the sphere is chosen to be 1 mm, corresponding to the largest particle in the measurement. It is clear that the scattering efficiency is much smaller than the absorption efficiency. Hence the snowpack can be treated as a lossy absorbing medium in the frequency range up to 10 GHz.

Next, let us check the effect of the small hole on the transmission measurement system and accuracy. The problem can be reduced to finding the propagation constant of normal modes that propagate in a hollow cylinder surrounded by a lossy dielectric medium, and comparing it to the propagation constant of a plane wave that propagates in the snow medium. In order to check quantitatively and exactly as much as possible, we model the hole as a circular hollow cylinder of radius a as shown in Fig. 10. The diameter of the air-filled cylinder is 2 cm in the measurement.

The lowest attenuated mode in this structure is the dominant HE_{11} mode [14], [15]. All we have to do is to cal-

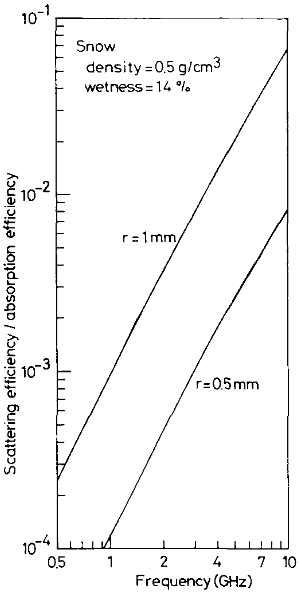


Fig. 9. Ratio of scattering to absorption efficiency as a function of frequency.

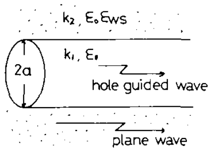


Fig. 10. Circular hollow cylinder in lossy medium.

culate the propagation constant of the dominant mode based on the following equation:

$$\left(\frac{J_n'(u)}{uJ_n(u)} - \frac{H_n'(v)}{vH_n(v)}\right)\left(\frac{k_1^2 J_n'(u)}{uJ_n(u)} - \frac{k_2^2 H_n'(v)}{vH_n(v)}\right) = n^2h^2\left(\frac{1}{u^2} - \frac{1}{v^2}\right)^2 \quad \text{(A5)}$$

where

$$u = \sqrt{k_1^2 - h^2 a}, \qquad v = \sqrt{k_2^2 - h^2 a}$$

$$k_1 = \frac{2\pi}{\lambda}, \qquad k_2 = k_1\sqrt{\epsilon_{ws}}$$

$$\epsilon_{ws} = \epsilon'_{ws} - j\epsilon''_{ws}, \qquad h = \alpha - j\beta$$

h	propagation constant,
α	attenuation constant,
β	phase constant,
u^2	$(k_1^2 - h^2)a^2$, $v^2 = (k_2^2 - h^2)a^2$,
k_1	$2\pi/\lambda$, $k_2 = k_1\sqrt{\epsilon_{ws}}$,
ϵ_{ws}	$\epsilon'_{ws} - j\epsilon''_{ws}$,
$J_n(u)$	Bessel function of order n,
$H_n(v)$	Hankel function of the second kind of order n,
$'$	differentiation with respect to the argument u or v.

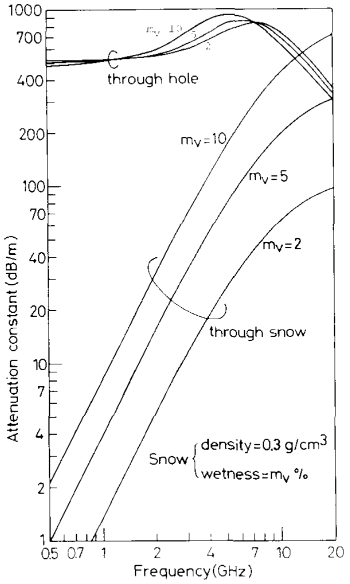


Fig. 11. Comparison of attenuation constants for the hole-guided wave and the plane wave in a snowpack.

The computed results are shown in Fig. 11, coupled with the attenuation of the plane wave in snow. The parameters are chosen to be:

snow density = 0.2–0.5
snow wetness = 2–10%
radius of the hole a = 1 cm.

The snow parameter yields the complex dielectric constant of snow particle (see (1)–(4)).

On the other hand, the attenuation of the plane wave propagating in the lossy homogeneous medium is given by the following equation:

$$\alpha = -2\pi/\lambda \ \mathrm{Im}\,(\sqrt{\epsilon_{ws}}) * 8.686 \ (\mathrm{dB/m}). \quad \text{(A6)}$$

From Fig. 11, it is understood that the attenuation constant of the dominant mode which propagates along the small hole is much larger than that of the plane wave in the snow medium in the frequency range from 500 MHz to 10 GHz. Hence we do not have to take into account the hole effect on the microwave transmission measurement.

Based on the above theoretical results, we applied simple transmission line theory to the snowpack for the analysis of transmission loss. Since the transmission loss analysis of a multiple cascaded line is well known and available in any textbook such as [12], [13], we omit the theoretical expression of the transmission loss as well as the formulation.

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