Snow dielectric properties: from DC to microwave X-band

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ABSTRACT. Broadband measurements of dielectric properties of natural snow samples near or at 0°C are reported. Measurement quantities are: dielectric permittivity, loss factor and complex propagation factor for electromagnetic waves. X-band measurements were made in a cold room in the laboratory; measurements at low and intermediate frequencies were carried out both in the field (Stubai Alps, 3300 m; Hafelekar near Innsbruck, 2100 m) and in the cold room. Results show that in the different frequency ranges the relative effect on snow dielectric properties of the parameters: density, grain-size and shape, liquid water content, shape and distribution of liquid inclusions and content of impurities, varies significantly. In the low-frequency range the influence of grain-size and shape and snow density dominates; in the medium-frequency range liquid water content and density are the dominant parameters. In the microwave X-band the influence of the amount, shape and distribution of liquid inclusions and snow density is more important than that of the remaining parameters.

INTRODUCTION

Measurements of the spectral behaviour of the dielectrical properties, especially in the X-band, have been reported by several authors, with somewhat inconsistent results. The peak of the losses has been found not only at ≈ 10 GHz (Hallikainen and others, 1982; Mätzler, 1987) but also at frequencies higher than 12 GHz (Linlor, 1980). In addition, experimental evidence of magnetic effects ($\mu' \leq 1$ and $\mu'' \geq 0$) induced by ring-shaped water inclusions has been reported (Mätzler, 1988). The aim of this work was to study the relative influence of such different parameters as porosity, density, liquid content and shape, grain-size and shape on the dielectric behaviour of natural snow samples over a wide frequency range. By measuring the complex reflection and complex transmission coefficient in the microwave X-band, dielectric and magnetic properties have been derived separately.

MEASUREMENT TECHNIQUES

Different measurement techniques have been used to measure the dielectric permittivity of snow in the different frequency ranges. In the low-frequency range from 10 Hz up to 50 MHz measurements were made with a simple plate condenser (consisting of 5 or 8 plates; dimension $6 \times 7 \, \text{cm}^2$ with a spacing of 1.5 cm) as sample holder and a low-frequency automatic network analyzer (ANA), type R&S ZPV with tuner unit E1 (Rohde and Schwarz, 1978). The frequency dependence of the sensor impedance in snow is automatically and continuously recorded. A block diagram of the experimental setup is given in Figure 1a. From the complex ratio of the
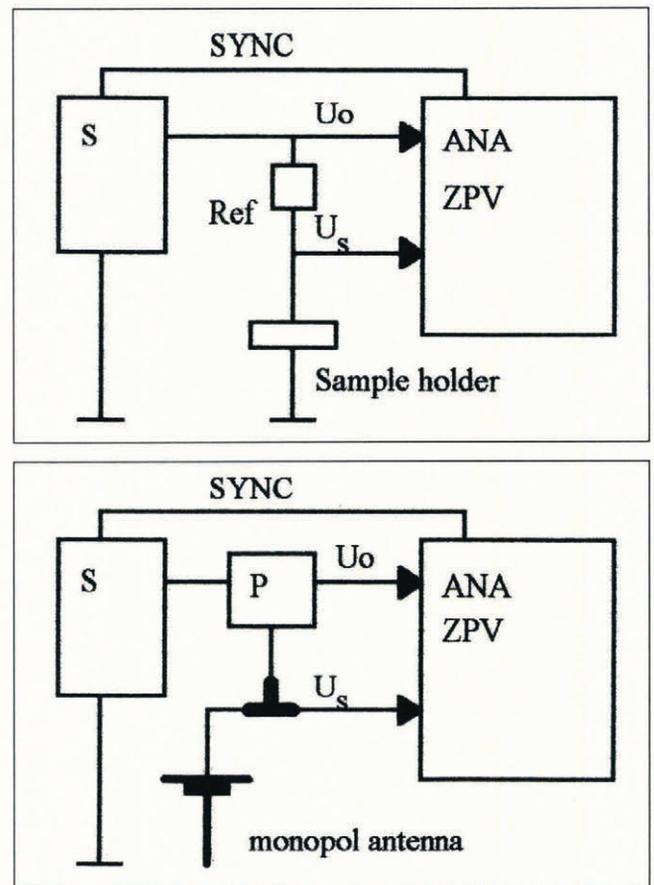
Fig. 1. Block diagram of the measuring systems. a, low-frequency. S, sweeper; ANA, automatic network analyzer ZPV; SYNC, synchronisation; U_o, U_s, measured signals; Ref, reference impedance. b, intermediate frequency. S, sweeper; P, power splitter; ANA, automatic network analyzer ZPV; U_o, U_s, measured signals.

measurement voltages, U_o and U_s, the dielectric function can be calculated.

In the intermediate frequency range from 50 MHz to approximately 1.5 GHz measurements were made with a set of monopol antennas as resonators (Denoth and Foglar, 1986) together with the network analyzer ZPV and tuner unit E3, whereby a specific measuring system, denoted as T-method, was applied (Rohde and Schwarz, 1978). From the measured change of sensor resonance frequency between that in air and with the sensor in snow, and from the measured change of half width of the resonance curve, the dielectric function was calculated. A block diagram of the experimental setup is given in Figure 1b.

In the microwave X-band a "free space measurement technique" was applied by using a high-frequency network analyzer (type HP8510A). This method was preferred, because it allows measurements on large snow samples with dimension $50 \times 50 \, \text{cm}^2$ cross section and different thicknesses to average over possible snow inhomogeneities. A block diagram of the X-band measurement setup is given in Figure 2. From the measured complex reflection coefficient R and the
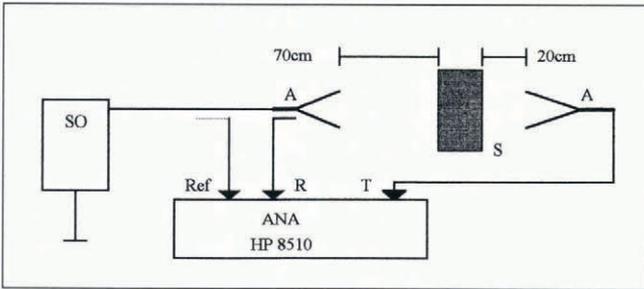
Fig. 2. Block diagram of the X-band measuring system. SO, sweeper oscillator; ANA, automatic network analyzer; S, sample; A, horn antennas; Ref, reference signal; R, reflected signal; T, transmitted signal.

complex transmission coefficient T, which includes effects of multiple beam interference (Azzam and Bashara, 1977), the dielectric function of snow was derived.

For interpretation of snow dielectric function, such texture parameters as snow density ρ, grain-size and shape, liquid water content W and liquid shape have to be known. Snow density was measured by weighing a known volume of a snow sample. Grain-size and shape were derived from an analysis of snow photographs (Denoth, 1982). Liquid water content W was measured using a freezing calorimeter, whereby the relative measuring error was found to be approximately 0.7 Vol.% for measurements in the laboratory and ≈ 1 Vol.% for field measurements. In addition to these measurements snow liquid water content was also measured using a calibrated dielectric sensor, whereby the relative error was found to be ≈ 0.2 Vol.%.

EXPERIMENTAL SNOW DIELECTRIC DATA

Measurements were made with different snow samples, which were classified according to grain-size and shape.

Snow samples with well rounded grains, grain-size $> 0.5 \, \text{mm}$, were denoted as old coarse-grained snow. Fine-grained snow samples (grain-size $< 0.5 \, \text{mm}$) with a
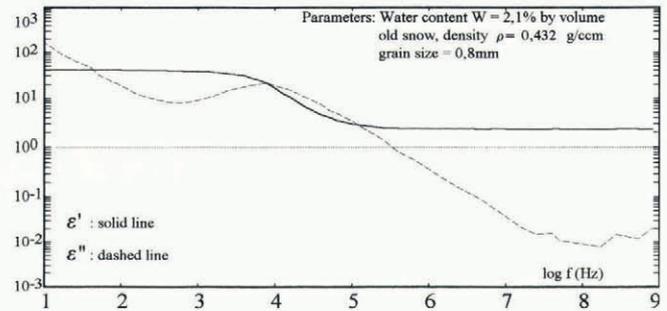
Fig. 3. Dielectric function of snow in the low and intermediate frequency regime.

plate-like and/or needle-like shape of the grains were denoted as new fine-grained snow.

The principle behaviour of permittivity and the loss factor of snow in the frequency regime from 10 Hz to 1 GHz is shown in Figure 3. Due to the relaxation process of the ice component near 10 kHz, permittivity decreases from its static value to a relatively low but frequency-independent value in the range of 1 MHz to approximately 1 GHz. The low-frequency losses are determined by ionic conductivity and by the dielectric loss of the ice
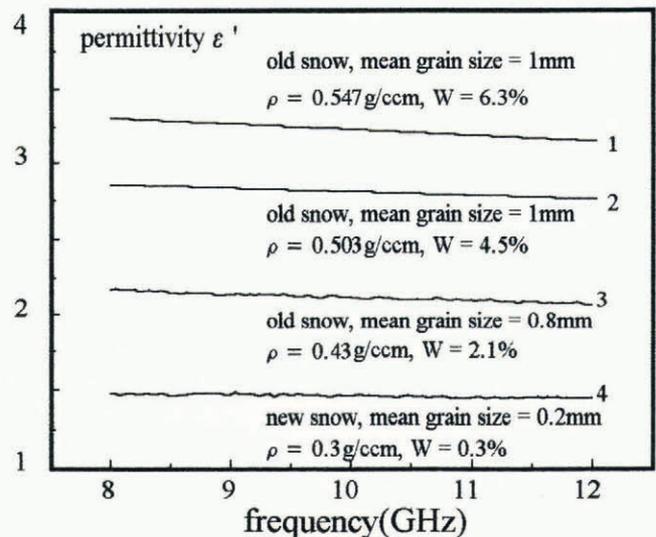
Fig. 4. Permittivity ϵ' of snow between 8 and 12 GHz.

component. In the MHz regime the losses are very low even if the snow is wet. In the microwave X-band measurements were made with moderately wet natural snow samples. The dielectric function, ϵ' and ϵ'', of four selected snow samples is shown in Figures 4 and 5. In general, snow permittivity shows a slight decrease with increasing frequency, the loss factor shows a slight increase with increasing frequency. Except in sample 4 (new fine-grained snow, $\rho = 0.3 \, \text{g cm}^{-3}$, $W = 0.3\%$) a

Fig. 5. Loss factor ϵ'' of snow between 8 and 12 GHz.

Fig. 7. Dependence of static dielectric constant on water content.
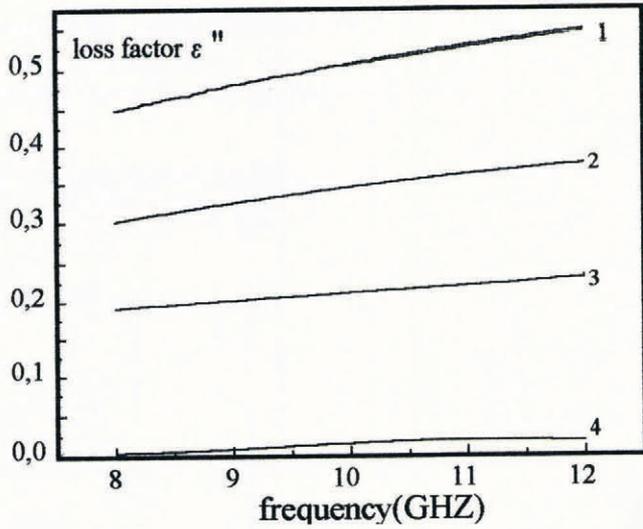
maximum of the losses in the microwave X-band was not observed. In addition, no significant deviation from $\mu' = 1$ and $\mu'' = 0$, as a possible magnetic effect of ring-shaped water inclusions, was detected.
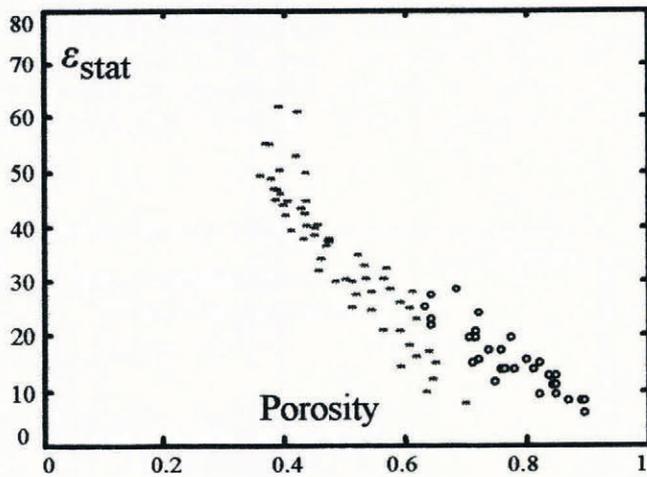
Fig. 6. Dependence of static dielectric constant on porosity. (Open symbols, new fine-grained snow; asterisks, old coarse-grained snow.)

RESULTS AND CONCLUSIONS

Snow dielectric data in different frequency regimes have been analyzed with respect to the effects of porosity, density, water content and type of snow (grain-size and shape). Results of measurements are given for three selected frequencies: $< 1 \, kHz$ (static values), 10 MHz and 10 GHz, respectively. Figure 6 shows the dependence of the static dielectric constant on snow porosity, whereby the type of snow plays an important role. Figure 7 shows the influence of the liquid water content. Due to the similar static permittivity of ice and water only a weak influence of liquid water content was observed.

Figure 8 shows the dependence of the incremental permittivity $\Delta\epsilon'$ on water content at a measurement

frequency of 10 MHz, whereby $\Delta\epsilon'$ is defined as:

$$\Delta\epsilon' = \epsilon_{\text{measured}} - 1 - 1.76(1 - \Phi) - 0.37(1 - \Phi)^2$$

$\Delta\epsilon'$ depends on water content but no significant effect of grain-size or shape was observed. Figure 9 shows the dependence of the loss factor ϵ'' on snow porosity. ϵ'' shows a strong dependence on both snow porosity and snow type; a significant influence of water content, however, could not be found. The comparable higher losses of new fine-grained snow may be due to the relatively larger surface of the ice grains, surface conductivity possibly increasing in importance.
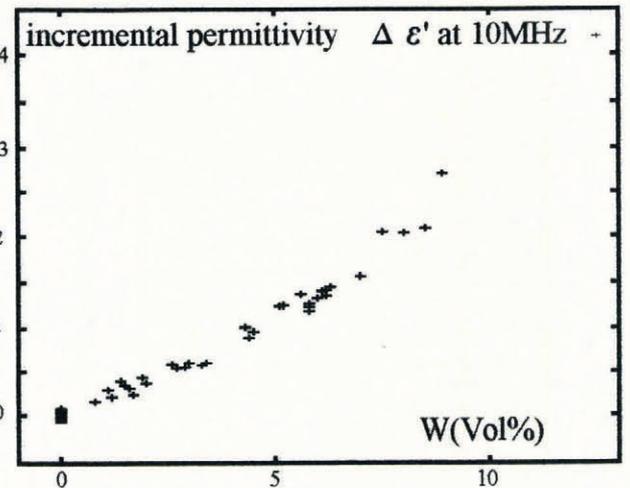
Fig. 8. Incremental permittivity $\Delta\epsilon'$ for new fine-grained and old coarse-grained snow.

Results of X-band measurements are shown in Figures 10 and 11. Figure 10 shows the dependence of the incremental permittivity $\Delta\epsilon'$ (10 GHz) on water content. Figure 11 gives the dependence of ϵ'' on liquid content for new fine-grained and old coarse-grained snow samples.

No significant effect of the type of snow on $\Delta\epsilon'$ (10 GHz) was found. Water content is the dominant parameter; calculations of $\Delta\epsilon'$ based on the Polder and
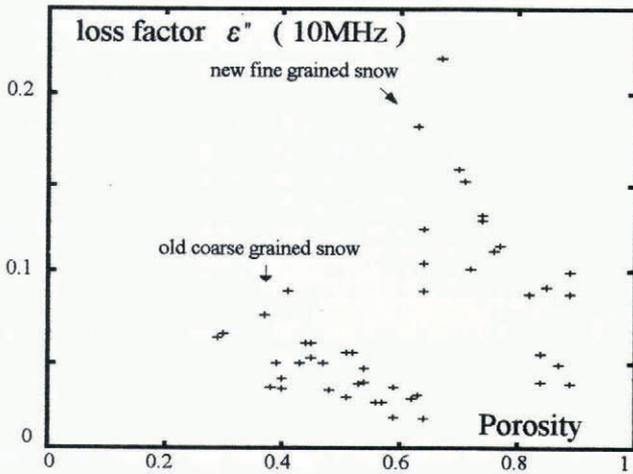
Fig. 9. Loss factor ϵ'' for new fine-grained and old coarse-grained snow.
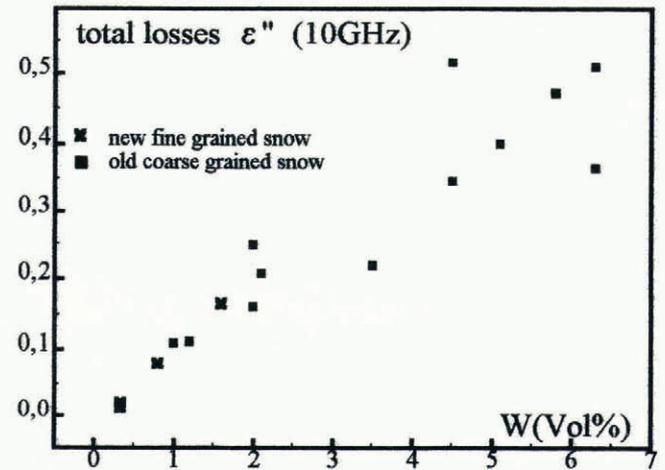
Fig. 11. Loss factor ϵ'' for new fine-grained and old coarse-grained snow.
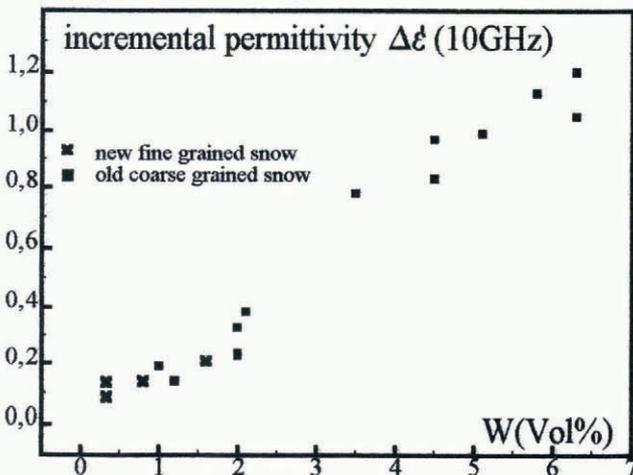
Fig. 10. Incremental permittivity $\Delta\epsilon'$ for new fine-grained and old coarse-grained snow.

van Santen (1946) theory indicate a weak influence of the shape of the water component. The loss factor ϵ'' (10 GHz) shows a strong dependence on water content. Again, model calculations indicate an influence of the shape of water component. This theory predicts, however, a considerable shift in the apparent relaxation frequency which has not always been observed. So, scattering as an additional effect should be considered and modelling of ϵ'' data based solely on water content and shape factors seems not to be sufficient.

The relative importance of the parameters porosity, liquid content, liquid shape, grain-size and shape in the different frequency regimes is summarized in Table 1.

ACKNOWLEDGEMENTS

Table 1. *Relative importance of the parameters porosity, liquid content, liquid shape, grain-size and shape for the dielectric function of snow*

Dielectric function	ϵ'	ϵ''
	low-frequency regime: < 1 kHz	
Important	grain-size and shape; porosity	impurities (DC-conductivity)
Less important	liquid content	—
Not important	liquid shape	—
	10 MHz	
Important	liquid content; porosity	grain-size and shape; porosity
Less important	liquid shape	impurities?
Not important	grain-size and shape	liquid content
	10 GHz	
Important	liquid content; porosity	liquid content and shape
Less important	grain shape; liquid shape	scattering? impurities?
Not important	—	porosity

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