MICROWAVE SENSOR FOR SNOWPACK WETNESS AND DENSITY PROFILE MEASUREMENT

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ABSTRACT

A microwave sensor for fast field measurements of snowpack wetness and density profiles is described. The sensor is an open resonator that can be pushed into snow. The resonant frequency (around 1 GHz) and the Q factor are automatically measured as a function of depth and converted to wetness and density values.

1. INTRODUCTION

Information about the wetness (liquid water content) and density of snow is important for snow studies and for remote sensing of snow [1]. Present wetness measurement methods such as cold and hot calorimeter methods are complicated and time consuming. They are inaccurate when the wetness by weight is less than a few percent and are not suitable for snowpack wetness and density profile measurements.

In remote sensing studies of snow the dielectric properties of snow are needed as a basis of ground truth data. On the other hand the dielectric properties are determined by the density and wetness. Hence it was decided to develop a sensor which can be used to measure in the field the dielectric properties of a snowpack as a function of depth. A suitable sensor is an open resonator which can be pushed into the snow. Its resonant frequency and Q factor are related to the dielectric properties of the surrounding material. When a correspondence between the dielectric properties and the density and the wetness is known the sensor can also be used to measure wetness and density.

2. DIELECTRIC PROPERTIES, WETNESS AND DENSITY OF SNOW

Several formulas and models describing the permittivity $\varepsilon_s = \varepsilon_s'(1 - j\tan\delta_s)$ of snow with given physical properties have been presented. The values given by different formulas are often inconsistent, but so are the experimental results [1], [2]. This is due to difficulties both in obtaining the real physical parameters and in measuring the electrical properties. In the following a relatively simple formula for the permittivity of snow will be used

$$(\varepsilon_s)^\alpha = \sum_c f_c(\varepsilon_c)^\alpha \quad , \tag{1}$$

where ε_s is the relative dielectric constant of snow
ε_c is the relative dielectric constant of snow components (ice, water, air)
f_c is the volume fraction of the corresponding component ($\sum f_c = f_i + f_w + f_a = 1$)
α is 0.4, an empirical constant.

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Formula (1) has been found to agree best with many experimental results in the case of wet snow. When the density and the wetness are substituted in (1) it gives

$$\varepsilon_s = \left[\left(\frac{\rho_s}{917} - \frac{W_{vol}}{0.917}\right)(\varepsilon_i)^{0.4} + W_{vol}(\varepsilon_w)^{0.4} + \left(1 - \frac{\rho_s}{917} + 0.09\,W_{vol}\right)\right]^{2.5}, \quad (2)$$

where ρ_s is the density of snow in kg/m^3
W_{vol} is the volume fraction of water.

Figure 1 shows the complex dielectric constant in the ρ-W-plane calculated applying formula (2) at a frequency of 1 GHz. In Figure 1 W_W is the water content or the wetness of snow by weight.

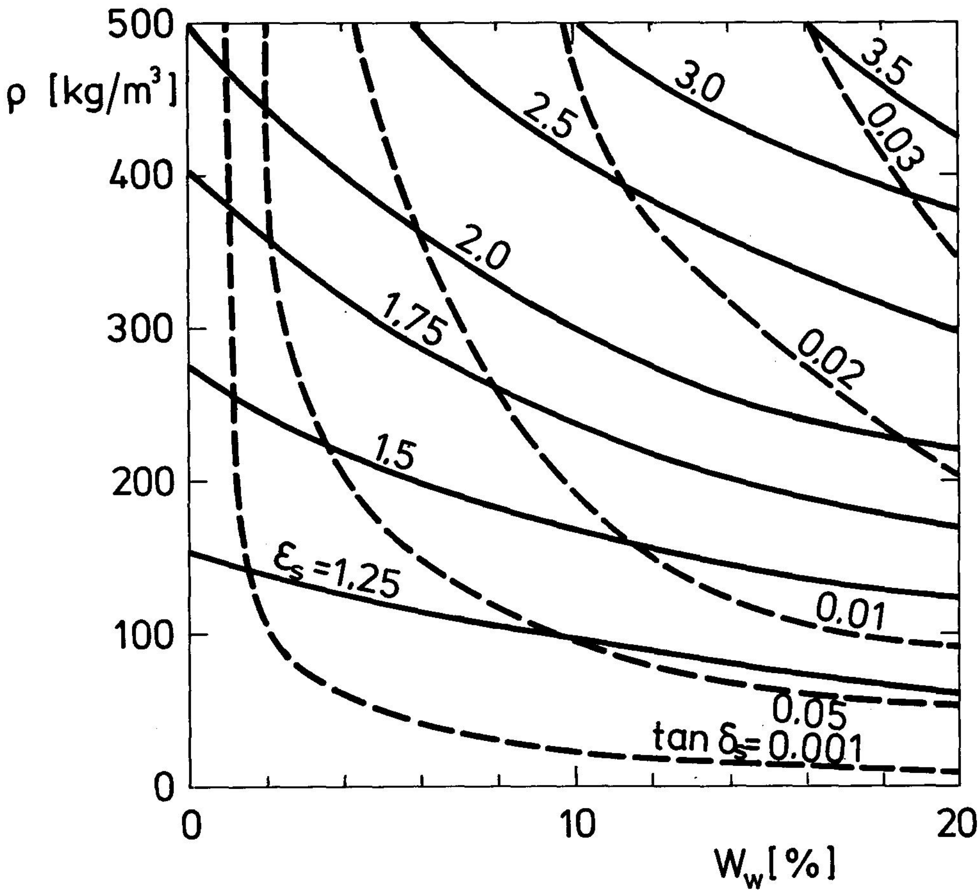

Figure 1. Relation between the dielectric properties (ε_s and $\tan\delta_s$) and the density (ρ) and the wetness of snow by weight (W_W) at 1 GHz.

The model gives the following formulas for the dielectric properties of snow around 1 GHz at 0°C

$$\varepsilon_s \approx A(\rho, W_w) \quad (3)$$

$$\tan\delta_s \approx B(\rho, W_w)\cdot f + C(\rho, W_w) \quad , \quad C \ll B\cdot f \text{ when } W_w > 1 \text{ percent.} \quad (4)$$

The real part is independent of frequency. The loss factor is proportional to the frequency at wetnesses greater than one percent. If the loss factor is known at a certain frequency f near 1 GHz the corresponding loss factor at 1 GHz is obtained by multiplying it with $10^9/f$. Hence Figure 1 can be used to obtain the density and the wetness from the measured values of the dielectric constant.

3. THE SNOW SENSOR

The sensor developed at the Radio Laboratory consists of a resonator that can be pushed into snow. The resonant frequency and the Q factor of the resonator depend on the complex dielectric constant of the snow. Knowing the dielectric constant, the wetness and the density of the snow can be obtained using a suitable snow model.

The resonator (Figure 2) is a parallel wire transmission line resonator, open in one end and shorted in the other. A frequency around 1 GHz was chosen as the dimensions of the resonator are then suitable. The resonator is connected to the electronics through two thin rigid coaxial cables and coupling loops. The transmission loss is measured as a function of frequency. The real part of the dielectric constant is

$$\varepsilon_s' = \left(\frac{f_a}{f}\right)^2 , \qquad (5)$$

where f_a is the resonant frequency in air and f is that in snow.

When the coupling is made loose enough (transmission loss > 25 dB) the measured Q factor in air, Q_a, can be regarded as the unloaded Q_o. Q_a is between 40 and 70 depending on the separation between the wires. The loss tangent of the snow is then

$$\tan\delta_s = \frac{1}{Q_s} - \frac{1}{Q_a} , \qquad (6)$$

where Q_s is the Q factor measured when the sensor is in the snow.

The sensor is made of stainless steel to form a rigid structure that can be pushed without damage through a possible crust on the snowpack. The coupling loops are protected by epoxy plastic and the coaxial cables are protected and supported by a fiber glass pipe.

$Q \sim l/d$ $f_{air} \simeq 1\,GHz$

in snow:

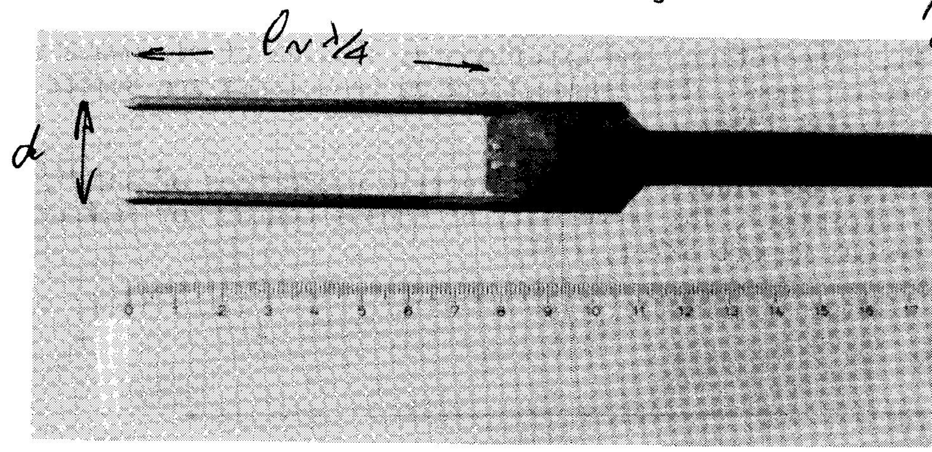

Figure 2. A snow sensor (an open resonator with a resonant frequency in air about 1 GHz).

4. THE MEASURING SYSTEM

A block diagram of the measuring system is shown in Figure 3. The system consists of a voltage controlled oscillator and electronics for automatic measurement of the resonant frequency and the 3 dB bandwidth. These values and information about the depth of the sensor in the snowpack can be recorded on tape in the field using a lightweight instrumentation recorder. The profile recording is made later in the laboratory using an x-y recorder.

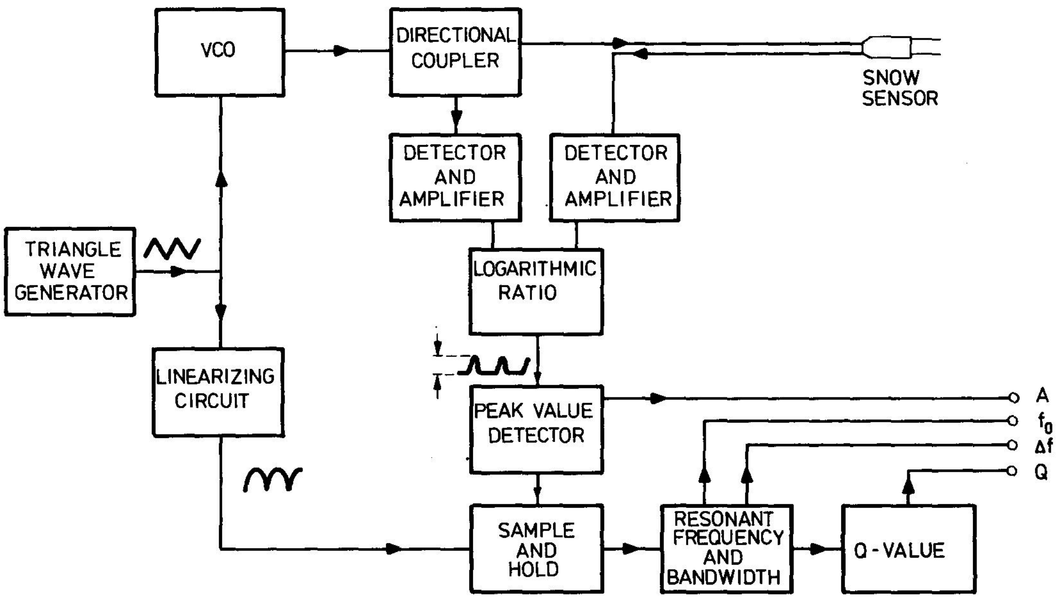

Figure 3. A block diagram of the sensor electronics for automatical measurement of the resonant frequency and the Q factor.

The accuracy of the measurement of the real part of the dielectric constant is about ±0.05 and that of the loss tangent is about ±0.001. Hence the theoretical accuracy of the wetness measurement around one percent wetness is about ±0.5 percent and still better at higher wetness rates.

REFERENCES

1. Tiuri, M., "Theoretical and experimental studies of microwave emission signatures of snow", IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-20, Jan 1982.

2. Stiles, W.H. and Ulaby, F.T., "Dielectric properties of snow", Remote Sensing Laboratory, The University of Kansas Center for Research, Inc., RSL Technical Report 527-1, 1981.