

DESIGN AND ANALYSIS OF AN ARRAY OF SQUARE MICROSTRIP PATCHES FOR  
NONDESTRUCTIVE MEASUREMENT OF INNER MATERIAL PROPERTIES OF VARIOUS  
STRUCTURES USING SWEEPED MICROWAVE FREQUENCIES

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INTRODUCTION

There are several microwave techniques and probes available for characterizing inner properties of materials [1]. Microstrip patches operating in cavity modes are well suited for determining the dielectric properties of materials. A microstrip patch can be characterized by its resonant frequency and quality factor (Q-factor) when operating in free-space. When the patch is covered by another material whose dielectric properties (real and imaginary parts) are different than that of free-space, resonant frequency and Q-factor of the patch will change. The changes in these two parameters are then related to the real and imaginary parts of the material permittivity. Subsequently, the permittivity of the material is related to its moisture content, density, temperature, grain size, etc. via available dielectric mixing models [2]. Such a device can be placed inside a material temporarily (snow pack for avalanche prediction) or permanently (concrete structures for water content and crack detection).

The motivation for this effort has been to design an array of microstrip patches to obtain a profile (snow permittivity vs. snow depth) of the inner properties of a material via a single measurement. This enables the operator to cause the least amount of destruction to the material. In designing such an array of the proximity effect of the patches causes undesired field coupling among patches which results in erroneous results. By designing different size patches which resonate at different frequencies, this problem can be alleviated. This paper gives the detailed design of such an array.

MICROSTRIP PATCH AND FREQUENCY MODES

An example of a square microstrip patch is shown in Figure 1. The length is slightly shorter than the width because the  $TM_{10}$  mode polarization of the patch is parallel to the length and radiation occurs from the fringing fields, thus the patch is effectively a square. Microstrip patches are modeled as cavity resonators. When a patch resonates it produces only transverse magnetic field (TM mode) because the electric field is directed perpendicular to the plane of the microstrip patch, while the magnetic field is directed along the plane of the strip [3]. Since the thickness of the dielectric substrate is much smaller than the operating wavelength, the TE mode will not exist. The  $TM_{10}$  mode is chosen to be excited as this is the dominant mode of

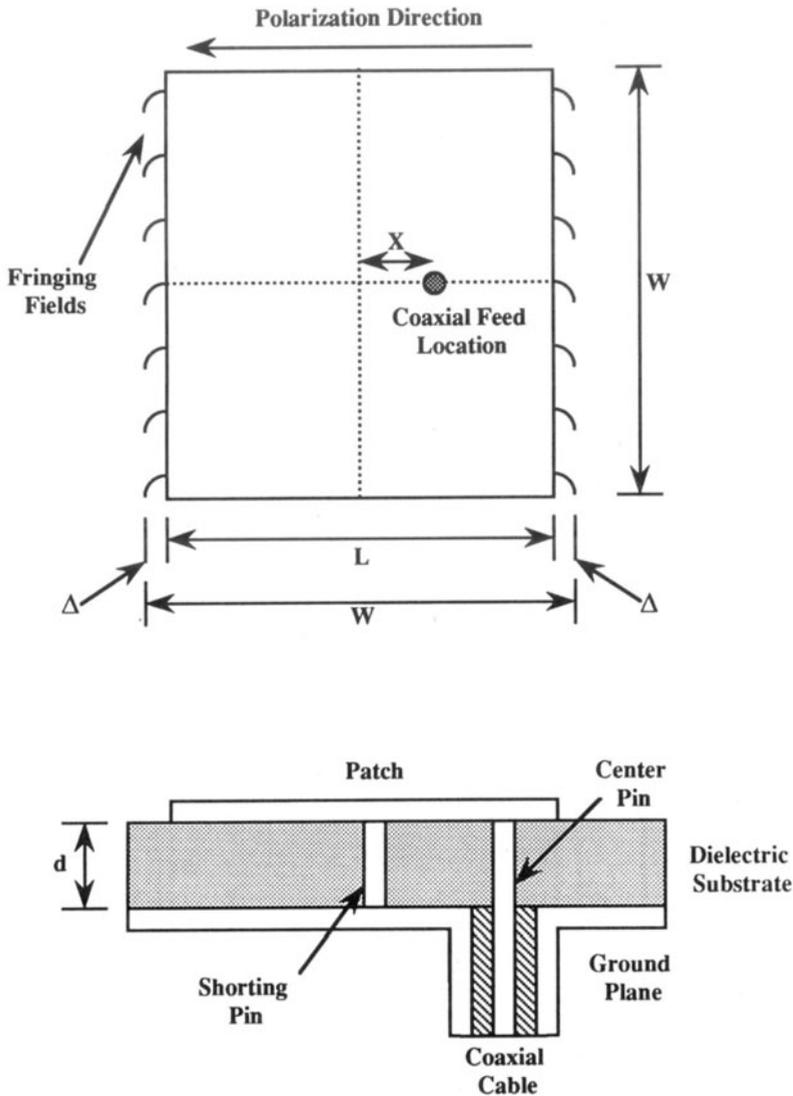


Fig. 1. Plan and cross-section views of a typical microstrip patch.

operation in microstrips. Since the  $TM_{10}$  mode is propagated, fields will exist only in one direction, and a transmission line model may be used to predict the patch parameters [4].

#### RESONANT FREQUENCY

The resonant frequency of a rectangular patch is given by:

$$f_r = \frac{c}{2W\sqrt{\epsilon_r}} \quad (\text{Hz}) \quad (1)$$

where,  $W$  is the patch width,  $\epsilon_r$  is the relative permittivity of the substrate and  $c$  is the speed of light. The relative permittivity is that of the substrate (2.17 for this case) as compared to that of air. However, when the patch is surrounded by another medium (snow, soil, concrete), the relative permittivity is that of the substrate compared to that of the medium. Thus, the relative permittivity decreases as the permittivity of the medium surrounding the patch changes. Consequently, the resonant frequencies of the patch changes. This corresponds to a range of resonant frequencies as the medium in which the patch is operating changes, for example from light to dense snow or dry to moist concrete. Figure 2 shows the resonant frequencies of a 1.6 cm square patch with substrate dielectric constant of 2.17 as it operates in snow with dielectric constant ranging from 2.6 to 4.7.

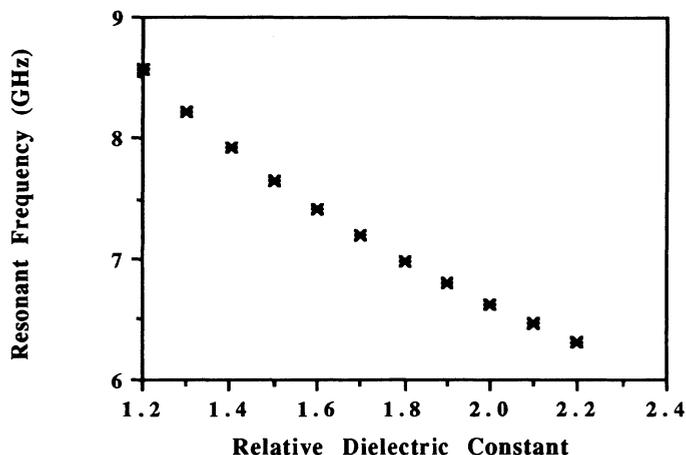


Fig. 2 Resonant frequencies of a 1.6 cm square patch when surrounded by snow ranging in dielectric constant from 2.6 to 4.7.

#### QUALITY FACTOR

The Q-factor of a microstrip patch is defined as:

$$Q = f_r / \Delta f = \text{Resonant Frequency} / 3\text{-dB Bandwidth}$$

$$\frac{1}{Q} = \frac{1}{Q_c} + \frac{1}{Q_r} + \frac{1}{Q_d} \quad (2)$$

where  $Q_c$  depends on the conductor losses,  $Q_d$  depends on the dielectric losses and  $Q_r$  depends on the radiation losses. The Q-factor for a patch is derived from the solution of Maxwell's equations subject to boundary conditions which is a tedious and complex process. A numerical approximation derived by Chew was modified and used for our case [5]. For a substrate of 1.59 mm thick (available commercially) the results were compared with published data for the Q-factor of  $TM_{10}$  mode and good agreement was obtained.

The Q-factor varies with changing permittivity. It is larger (the bandwidth of the resonant curve is smaller) for an increasing permittivity. The most significant problem encountered in this design is finding a way to feed each patch without exciting other patches as each patch has a certain bandwidth (Q-factor). This was accomplished by manipulating the patch sizes and thus the resonant frequencies in order to obtain the maximum number of patches that would not have overlapping resonant frequencies. The maximum and minimum resonant frequencies in a given range were calculated using permittivity of 1 (air) and 1.8 (dense snow). The bandwidth of each patch at those frequencies was overlaid to obtain the final frequency range for each patch. Figure 3 shows four patches that can operate within 2-9 GHz range without interfering with each other.

#### INPUT IMPEDANCE

The input impedance of a rectangular patch is given by:

$$R_e = \frac{1}{2G} \quad (\Omega)$$

$$G = \frac{\pi W}{\eta \lambda_r} \left[ 1 - \frac{(kd)^2}{24} \right] \quad (3)$$

where  $R_e$  is the input impedance of the patch,  $G$  is the conductance,  $\lambda_r$  is the resonant wavelength,  $\eta$  is the free-space impedance,  $k$  is the wavenumber and  $d$  is the thickness of the substrate. The input impedance was calculated for each patch and used to find the coaxial feed location.

#### COAXIAL FEED LOCATION

Two methods of feeding the patches were examined namely microstrip and coaxial transmission lines. Microstrip lines are very appealing as they can be fabricated along with the patches in one process. However, they have limited bandwidth of operation which limits their use in this design. Coaxial transmission lines on the other hand have very large

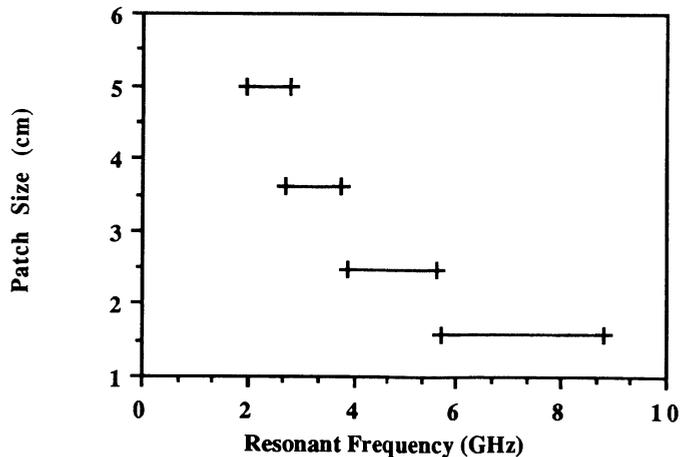


Fig. 3. The four designed patch sizes versus their resonant frequencies.

bandwidths and are well suited for this design. To minimize the reflection due to impedance mismatch at the feed point, the input impedance of the patch must equal the impedance of the coaxial transmission line feeding it. Thus, the location of feed point for each patch must be found to satisfy this requirement. The feed location of each patch as depicted in Figure 1 is calculated as:

$$x = \frac{L}{\pi} \sin^{-1} \sqrt{\frac{R_i}{R_e}}$$

$$L = W - 2\Delta \tag{4}$$

$$R_i = 50 \ \Omega$$

When the coaxial cable center pin is at this location, the impedance of the patch and the coaxial cable will be matched. The shorting pin placed at the center of the patches provide low frequency grounding of the patch without disturbing its microwave characteristics. For the modes operation there already exists a short circuit at this point [4].

#### POWER DIVIDER/COMBINER

A scheme to transfer the signal from the oscillator and split it into four separate signals to feed each patch with an available bandwidth of at least 7 GHz is desirable. Most power dividers have smaller bandwidth than required here. Nystrom has designed a binary divider which can be modified for our purpose. This is a binary power divider consisting of 2-way Wilkinson hybrids coupled after each other to form a symmetrical branching structure. This essentially consists of quarter-wave transformers with isolation resistors [6]. Figure 4 shows this power divider which is designed to operate at a center frequency of 5 GHz and a bandwidth from 1.5 to 9.5 GHz. The design parameters for a 1-4 wide-band power divider are given in Table 1.

Table 1. 1 to 4 Power Divider Parameters, VSWR = 1.2.

Input Impedance $Z/Z_i$	Isolation Resistor $R/R_i$
1.15	6.52
1.31	6.97
1.53	4.37
1.82	3.15
1.10	37.26
1.31	10.12
1.53	6.38
1.73	2.30

#### FINAL DESIGN

The final design is shown in Figure 5. It consists of a rectangular solid that has the patches on a printed circuit board place on it. Each patch is fed by a coaxial cable, and the cables are fed by a wide band sweep oscillator via a power divider. As mentioned the patches are designed to resonate within this wide frequency range without patches' resonant frequencies overlapping. The patches are located 6 inches

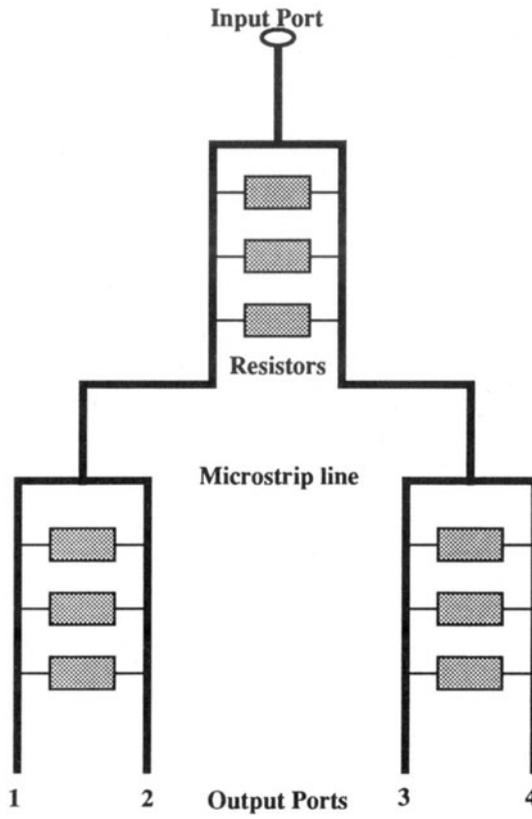


Fig. 4. Presentation of a binary power divider.

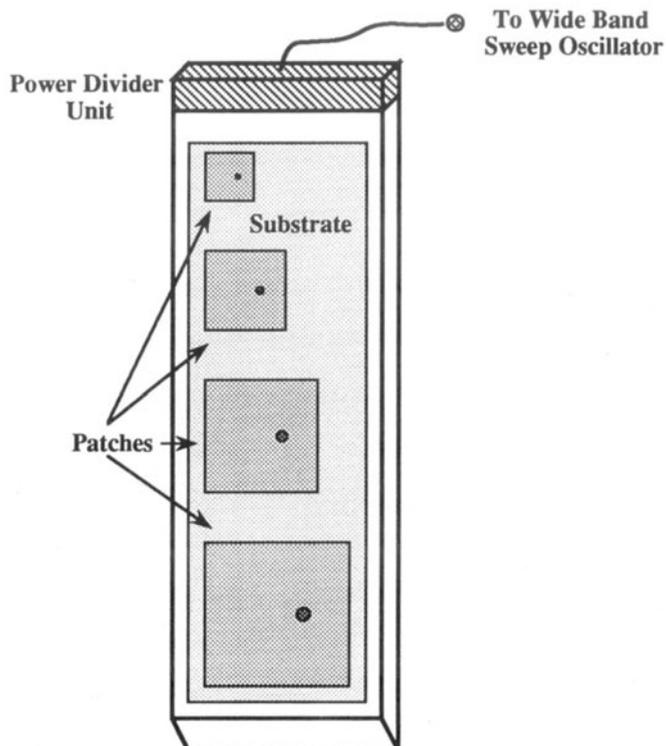


Fig. 5. The final configuration of the device (not to-scale).

TABLE 2. Patch Design Parameters.

a (cm)	X (mm)	Max. $f_r$	Min. $f_r$	Max. Q	Min. Q
1.60	2.77	8.81	5.70	20.1	14.5
2.46	2.46	5.60	3.86	28.9	21.8
3.62	6.38	3.76	2.69	45.3	31.6
5.00	8.87	2.77	1.97	62.4	43.4

apart, top edge to top edge. The printed circuit board will be approximately 2.5' long by 8" wide. Table 2 gives the final design parameters. The design allows for incorporation of modularity as multiple printed circuit modules and power dividers can be used in order to extend the monitoring depth (length of the device).

Modified versions of this device can be used to monitor physical parameters such as water content, density changes, structural cracks, etc. In the case where the media which is to be monitored does not allow a probe to be inserted into it, a sheet with patches on it can be placed in the media prior to manufacturing. Possible examples of this include

monitoring of water content of building materials, road bases, water table level.

#### CONCLUSIONS

The detailed design of a device for measuring dielectric properties of materials was outlined. It consists of an array of square microstrip patches which is a simple, problem specific and low cost design. It can be inserted into the medium or can be permanently placed within it. Resonant frequency and quality factor variations of these patches while operating in free-space and while surrounded by a different material are used to monitor the permittivity of the material. This device allows profile measurement of the dielectric properties. This device is well suited for applications in avalanche prediction, moisture content, crack development monitoring of concrete structures, etc.

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