A Cavity-Backed Slot Antenna on Timber

Mohamed Radwan

*School of Engineering and Built
Environment*

Griffith University

Brisbane, Australia

mohamed.radwan@griffithuni.edu.au

Yana Salchak

*School of Engineering and Built
Environment*

Griffith University

Brisbane, Australia

i.salchak@griffith.edu.au

Noor Albadri

*School of Engineering and Built
Environment*

Griffith University

Brisbane, Australia

n.al-badri@griffith.edu.au

Hugo G. Espinosa

*School of Engineering and Built
Environment*

Griffith University

Brisbane, Australia

h.espinosa@griffith.edu.au

David V. Thiel

*School of Engineering and Built
Environment*

Griffith University

Brisbane, Australia

d.thiel@griffith.edu.au

Abstract— Cavity-backed slot antennas can be used to detect anomalies and measure the dielectric properties of lossy media such as timber at microwave frequencies. An enhanced antenna design with the feed plate directly behind the rectangular slot allows maximum E-field coupling to the wood and provides more space for electronics inside the aluminum box. The E-field in a rectangular wood piece (100 mm × 70 mm × 70 mm) was calculated using CST simulations at the resonant frequency of 7.4 GHz. The wood material was modeled as isotropic with a relative permittivity of 2 and low conductivity (10^{-6} S/m). A comparison between simulations and a spherical wave calculation showed significant change in E-field in the very near-field region of the antenna at the distances smaller than 4 mm. The electrical field penetrated the 70 mm width, and reflection from the opposite wood-air interface was observed.

Keywords— slot antenna, non-destructive testing, structural timber, near field, microwave impedance.

I. INTRODUCTION

Microwave transmission has been used in testing wood for several years [1]. Timber is an anisotropic material and it is relatively transparent at microwave frequencies [2]. This opens an opportunity to study the anisotropic characteristics and dielectric properties of wooden beams at microwave frequencies using far-field measurements [1-4]. Saeidi et al. [5] applied near-field and far-field ultra-wideband (UWB) radio signals to image wood imperfections. Frequencies in the range of 1.25-1.35 GHz and 1.7-1.81 GHz were used in measurements of S-parameters (transmitted and received signals) performed in air, plywood and high-density wood. The results demonstrated that while the received signal amplitude changes, the pulse envelope does not change. This technique is adequate for imaging wooden beams when access is available to both sides of the wood with rectangular cross-section.

As reported in [6], three-dimensional numerical simulations using commercial software were performed to profile the electromagnetic field at 3 GHz inside a cylindrical wood structure. The study reported the effect of the wood grain angle, the circular annual rings, and the effective permittivity of wood on the electric field distribution inside the wood cylinder.

A planar resonant slot antenna with a ground plane aperture was developed to determine the complex permittivity of a dielectric material in [7]. Part of the electric field permeates the dielectric substrate and enters into free space

again through the slot. If an electric field penetrates a dielectric material (in this case wood), then computer simulations can reveal its behaviour inside that material for comparison with numerical calculations.

In this paper, a new feed for a slot antenna was designed and optimized for wood contact, based on a previously published antenna [8]. Experimental measurements and modelling using a cavity-backed slot antenna on concrete have also been used for electrical parameter measurements [9]. The calculations and antenna design were conducted using the commercial software CST Microwave studio©. The cavity-backed slot antenna was simulated as a rectangular box with a capacitively-coupled slot.

The slot dimensions and port position were adjusted to obtain the minimum S_{11} values on pine wood with relative permittivity $\epsilon_r = 2$. The S_{11} characteristics were adjusted by changing the relative permittivity in a previous model [10]. For a fixed relative permittivity of wood, a parameter sweep was applied in CST to determine the optimal location of the brass feed. At this position, a minimum reflection coefficient value was chosen to define the feed position and resonant frequency. The radiation pattern was determined inside the uniform pine wood beam based on simulations to calculate the electric field inside a wood piece with rectangular cross-section (dimensions 70×70×100 mm).

II. ANTENNA DESIGN

To achieve a minimum S_{11} at 50Ω, the antenna impedance was matched to the surrounding media – in this case, wood. The feed was located on the side opposite the slot (see Fig. 1) and optimized to give the lowest S_{11} value.

The antenna slot placed on wood is resonant when the slot length is approximately equal to one half of the effective wavelength:

$$l \cong \lambda/2 \quad (1)$$

where l is the slot antenna length and λ is the effective wavelength. The effective wavelength depends on the free space wavelength and the effective wood permittivity, and it can be approximated by the equation [9]

$$\lambda \cong \frac{\lambda_0}{\sqrt{\frac{1+\epsilon_r}{2}}} \quad (2)$$

where ϵ_r is the relative permittivity of wood and λ_0 is the free space wavelength. For dry wood, the relative permittivity lies in the range from 1.5 to 4 [11]. In simulations, the wood was defined as a lossy media with a density of 454 kg/m³, conductivity σ of 10⁻⁶ S/m, and a relative permittivity of 2 [11, 12].

The electric field $E(X)$ close to the antenna aperture penetrates wood according to the equation [13, 14]:

$$E(X) = E_o \frac{\exp(-\alpha X)}{X} \quad (3)$$

where E_o is the electric field strength on the surface of wood (V/m), X is the distance (m) from the surface of the wood and α is attenuation constant. By fitting the curve to equation (3), the attenuation constant α was calculated to be approximately 0.5 Np/m.

(a)

(b)

Fig. 1. (a) Top view (left) and side view of the cavity-backed slot antenna, (b) antenna model and brass position

III. NUMERICAL SIMULATIONS

The aluminum box ($W_b \times W_b \times H_b$) has a slot ($W_s \times L_s$) fed by a brass plate ($W_L \times L_L$) located directly behind the slot. The antenna dimensions are given in Table I. The design challenge was to determine the brass position (d_p) in Fig. 1 for a minimum S_{11} value with the slot against the flat surface of pine wood. By using CST parameter sweep function ($2 < d_p < 22$ mm), the minimum S_{11} value was found when $d_p = 13$ mm (see Fig. 2).

In CST, the antenna slot was placed against an isotropic pine woodblock ($70 \times 70 \times 100$ mm) with 454 kg/m³ [11], and a relative permittivity $\epsilon_r = 2$. The resonant frequency of the antenna on wood was 7.4 GHz with $S_{11} = -45$ dB (Fig. 3).

TABLE I. ANTENNA DIMENSION

Parameter	W_b	W_s	L_s	L_L	W_L	d_p	d	H_L	H_b
Value(mm)	33	9	21	4.5	8	13	4	3.25	11

Fig. 4 shows the comparison between CST results for E -field penetration inside the wood sample versus numerical calculations using (3) at 7.4 GHz through the wood, directly in front of the center of the antenna aperture. These simulations show that the wood sample has a relatively large change in the very near-field region of the antenna (i.e., $X < 4$ mm). There is also evidence of reflection from the opposite wood-air interface creating a standing wave.

Fig. 2. S_{11} simulated values for various brass feed positions d_p relative to the end of the cavity.

Fig. 3. Simulated S_{11} of the optimized antenna ($d_p = 13$ mm) against pine wood. The resonant frequency is 7.4 GHz.

Related published work from other researchers [3] noted average values of relative permittivity at 9.8 GHz for Poplar, Alder and Oriental beech woods between 1.1 and 4, depending on the moisture content. In the simulations presented in this paper, the relative permittivity was fixed at 2 and the attenuation constant $\alpha=0.5 \text{ Np/m}$ was relatively insignificant compared to the spherical wave field strength decrease.

Fig.4. Simulated E-field on CST (orange line) vs numerical calculations according to (3) (green line). The surface of the wood is at distance zero.

IV. CONCLUSIONS

The penetration depth of electromagnetic waves from a slot antenna on the surface of an isotropic woodblock, based on numerical calculations using CST, was approximately 4 mm from the wood surface. Beyond this distance, the field attenuates as an inverse square law as the conductivity is sufficiently low. Further work is required to explore the effect of wood anisotropy, the difference between wood types, the effect of moisture and finally the effect of discontinuities in wood beams.

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