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A Microwave Method for Measuring Moisture Content, Density, and Grain Angle of Wood

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Abstract

The attenuation, phase shift and depolarization of a polarized 4.81-gigahertz wave as it is transmitted through a wood specimen can provide estimates of the moisture content (MC), density, and grain angle of the specimen.

Calibrations are empirical, and computations are complicated, with considerable interaction between parameters. Measured dielectric parameters, however, correlate uniquely and repeatably with MC over a range of MC at least as great as 100 percent of the dry weight of the wood. Grain angle can be deduced reliably when the specimen thickness and MC are great enough to introduce sufficient dielectric anisotropy to appreciably depolarize the incident wave.

At present, the apparatus and techniques are very complex, but the principles developed by this research show the method to be feasible for nondestructive testing of lumber as it is produced.

Keywords: Microwave transmission, homodyne, nondestructive testing, moisture content, density, grain angle.

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Introduction

A major difficulty in the use of wood in engineered structures is uncertainty in the design data for the individual load-bearing members. This difficulty would vanish if each member could be rated reliably as to its mechanical quality, through the use of nondestructive tests. Because strength can be measured directly only through destructive testing, the basis for any nondestructive rating of strength is a correlation between strength and other properties that can be measured nondestructively. Some properties that correlate in a generally useful way to strength are density, moisture content (MC), and grain direction. This report gives a brief summary description of a microwave transmission method that shows promise for estimating rapidly and nondestructively these three factors for sawn lumber. These factors are essential if not sufficient for predicting with useful reliability the strength of a given structural piece. The objective of the research reported here was to develop the method and demonstrate its feasibility for in-line stress grading of structural lumber.

Theoretical Basis

The dielectric properties of wood, which determine its characteristics in transmitting electromagnetic waves, are strongly dependent on MC and density of the wood. In addition, the dielectric properties are anisotropic, following the structural anisotropy of the wood.

The speed of propagation, and therefore the wavelength, of an electromagnetic wave is reduced when it travels through matter. This reduction in speed is in proportion to the dielectric constant of the matter, With wood, the dielectric constant depends on the density and MC of the wood. The retardation of the speed of propagation, therefore, is an indication of the density and MC of the specimen. The retardation is measurable as a phase change in the wave as it is transmitted through the specimen.

As it is transmitted through the specimen, the wave also suffers a loss of intensity, caused by absorption and scattering of the energy. The intensity loss depends on the loss factor and thickness of the specimen, and the loss factor of wood depends on its density and MC.

Finally, when a linearly polarized wave enters the wood, the dielectric anisotropy of the wood causes the wave to become depolarized. The electric vector of the incident wave is resolved into components in the directions of the maximum and the minimum dielectric constant. When the thickness and the degree of anisotropy of the specimen are sufficient, the wave emerging from the specimen is effectively elliptically polarized with its minor axis in the direction of the maximum dielectric constant, which is essentially the direction of the grain. For lesser thickness or anisotropy, the polarization angle is less than the true grain angle by a factor defined as M, the depolarization index, in percent.

This report, therefore, describes a method for measuring the attenuation, phase change, and depolarization of a microwave beam as it passes through the specimen. These parameters interact extensively, so the data reduction is complicated. But roughly, the attenuation reflects predominantly MC, phase change reflects both moisture and density, and details of the depolarization indicate grain angle.

A complete description of the method was given by Yen (198 1).

Apparatus and Methods

We will give a very brief general description of the apparatus and methods. Essential details are available in the references (Ellerbruch 1965, King 1978; King and Yen 1981; Yen 1981).

Microwave power at 4.81 gigahertz (GHz) is generated by a reflex klystron, and radiated from a linearly polarized horn antenna. The radiation passes through the specimen essentially as a plane wave, and then is reflected back through the specimen from a small dipole tuned to the 4.81-GHz frequency. The reflecting dipole also modulates the reflected wave, as explained below. The reflected energy reenters the same horn antenna from which it was radiated. The transmitted and reflected signals are combined in a homodyne circuit (termed "homodyne" because the reference signal (the transmitted wave) and the received signal (the reflected wave) are of the same frequency).

To produce sensible output from the homodyne detector, the reflected wave is modulated in two ways simultaneously. First, the reflecting dipole is switched in and out of resonance at a lo-kilohertz (kHz) rate by means of a PIN diode at the midpoint of the dipole. The switching is done by cycling the diode between conducting and nonconducting states by a 10-kHz sine wave applied to it through high resistance leads. When the diode is conducting, the dipole is a strong resonant reflector; when it is nonconducting, the dipole reflection is greatly reduced.

Second, in addition to the 10-kHz amplitude modulation, a combined 300-Hz amplitude and phase-related modulation is produced by spinning the reflecting dipole at 9,000 revolutions per minute. A reference signal is derived from the shaft of the spinning dipole, which is compared to the phase of the 300-Hz modulation to indicate the polarization angle of the transmitted wave. The amplitude of the 300-Hz modulation indicates the ratio of the major to minor axes of the elliptically polarized transmitted wave.

The two signals, at the two modulation frequencies, derived from the homodyne detector are the actual data. From analysis of the amplitude and phase of these signals, and the specimen thickness, the two-dimensional dielectric tensor of the specimen can be constructed using iterative methods. The relationships between the terms of the dielectric tensor and the desired physical properties of the wood are empirical, and must be established independently by measurements on wood of known properties.

In making the measurements and computations, the incident wave is maintained normal to the specimen surface, and reflections from the specimen are accounted for in the computation. Only two-dimensional anisotropy of the specimen is assumed. Varying slopes of grain were simulated by rotating specimens around an axis through the microwave beam. The incident plane of polarization was either parallel or perpendicular to the grain, within ±20° or less.

A block diagram of the apparatus is given (fig. 1) without extensive comment. Detailed explanation of figure 1 would not be useful here; it can be found in the references (King and Yen 1981; Yen 1981).

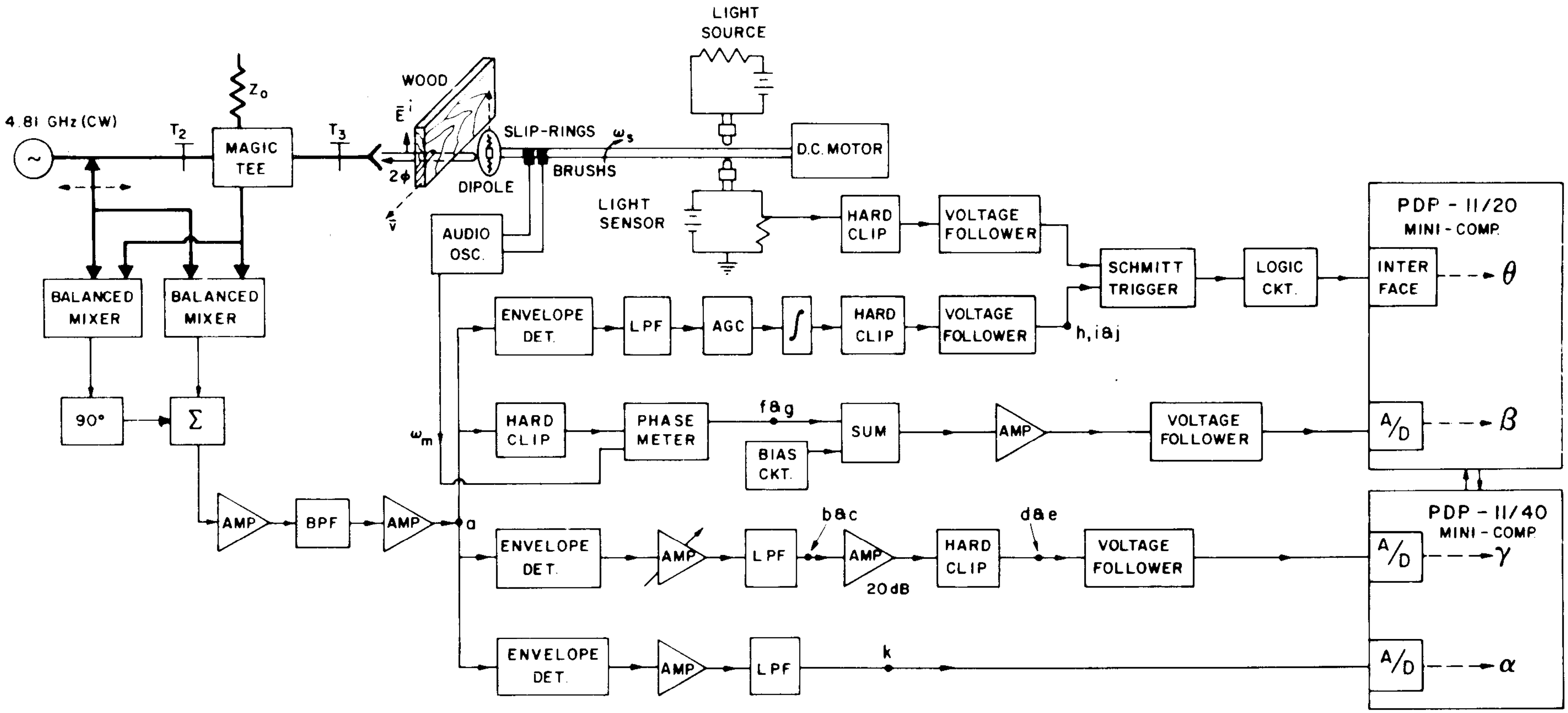

Figure 1.—Block diagram of the microwave system. The arrow touching the output line from the 4.81-gigahertz generator (upper left) represents a section of slotted wave guide from which is obtained a reference signal whose phase is adjusted by moving the probe in the slot. BPF = band pass filter and LPF = low pass filter. Output data (right side): Q = polarization angle, b = phase constant (phase shift in degrees per unit thickness). g = depolarization ratio (ratio of minor to major axis of polarization ellipse), and a = attenuation constant (power loss in decibels per unit thickness). (ML84 5826)

Experimental Results

Some preliminary measurements were made on a variety of specimens to determine how well the system responds to the pertinent wood properties. Data given represent the averages of several specimens and repeated measurements on each. Specimens used are described in table 1.

The electrical parameters were repeatable with good precision when the one-way transmission loss was no greater than about 20 decibels (power reduction by a factor of 100). The relationships between the electrical and physical parameters of the wood were similar for all specimens. Power loss and phase shift were essentially independent of grain angle if grain angle deviated from the incident polarization by no more than ± 20° (Yen 1981). (This is a very important result, as it greatly simplifies the data processing.) Power loss was predominantly affected by MC, the correlation being strongest when the incident polarization was nominally parallel to the grain. The correlation between power loss per unit thickness, α, and MC appeared to remain strong and nearly linear even to MC levels greater than 100 percent (fig. 2).

The phase shift per unit thickness, b, depended on both density and MC of the specimen (fig. 3), but the computations were able to infer density independent of MC.

When specimen thickness and MC were large enough, depending on the particular specimen, the polarization angle of the transmitted beam was a good indicator of the grain angle (figs. 4-6). At lesser MC and/or thickness, the depolarization of the incident beam was not complete, and the effective transmitted polarization angle was smaller than the grain angle by the factor M (fig. 4).

The analysis of data obtained by the present method yielded the two-dimensional dielectric tensor of the specimen (two instead of three dimensions because the radial and tangential directions were considered identical). For example, the dielectric tensors found for Douglas-fir at two different MC levels are as follows:

6 PERCENT MC

$$\begin{matrix} 2.35 - j0.15 & 0.0018 + j0.0075 \\ 0.0027 + j0.01 & 1.9 - j0.095 \end{matrix}$$

12 PERCENT MC

$$\begin{matrix} 2.73 - j0.7 & 0.0052 + j0.0078 \\ 0.0123 + j0.018 & 2.16 - j0.31 \end{matrix}$$

The two diagonal elements of this 2 x 2 tensor are the complex dielectric constants in the direction parallel to the grain and across the grain, respectively. The real (fig. 7) and imaginary (fig. 8) parts of these quantities are well correlated with MC over a range of MC extending to 100 percent or greater. The real part is the usual dielectric constant, and the imaginary part is often called the loss factor. The loss tangent (ratio of imaginary to real parts-fig. 9) also correlates clearly with MC, but the relationship is not as simple as that between MC and the real and imaginary parts separately.

The off-diagonal elements of the dielectric tensor quantify interaction between the parallel- and across-grain constants. These elements appeared to be particularly sensitive indicators of changes in MC (Yen 1981).

Table 1.—Properties of specimen material

Species	Specific gravity	Moisture content values	Thickness
		Pct	Cm
White pine	0.31-0.38	0, 6, 12, 204	1.5-5.08
Basswood	0.35	0, 6, 12	1.8
Aspen	0.38-0.41	0, 6, 12, 130	2.54-4.75
Douglas-fir	0.38-0.46	0, 6, 12, 31, 45, 52, 136, 150	0.7-5.08
Red oak	0.56-0.62	0, 6, 12	1.8-4.1
Hickory	0.72-0.73	0, 6, 12, 45, 48	2.4-4.5

Table 2.—Comparison[1] of dielectric constants from present study with corresponding data obtained previously[2]

Grain direction	Item	Present study[3]	James and Hamill
	6 PERCENT MOISTURE CONTENT		
Parallel	Dielectric constant	2.35	2.0
Parallel	Loss tangent	0.064	0.13
Perpendicular	Dielectric constant	1.9	1.8
Perpendicular	Loss tangent	0.050	0.065
	12 PERCENT MOISTURE CONTENT		
Parallel	Dielectric constant	2.73	2.85
Parallel	Loss tangent	0.26	0.22
Perpendicular	Dielectric constant	2.16	2.0
Perpendicular	Loss tangent	0.14	0.12

[1]Previous data interpolated to same frequency as present study.

[2]Data obtained using a slotted line method (James and Hamill 1965).

[3]Data derived from dielectric tensors (table 2).

The dielectric constant and loss tangent for Douglas-fir taken from the dielectric tensor obtained by the present method are compared here with corresponding values obtained earlier (table 2) using a slotted line method (James and Hamill 1965). The agreement is good considering the differences in specimen material and experimental methods.

For very wet and/or thick specimens, the transmission loss could be excessive. For such specimens, the necessary data could be derived from a reflected rather than a transmitted beam (Kraszewski and Kulinski 1976).

The depolarization appeared to be related to grain angle without significant confounding from the growth rings (Yen 1981).

The most persistent problem with this method, from a practical standpoint, is spurious reflection of microwave energy from the essential mechanical structures associated with the apparatus and specimen handling mechanism. Treatment of this problem includes covering the structures with microwave absorbers, and adjusting the microwave system to minimize its sensitivity to reflected energy other than from the spinning dipole.

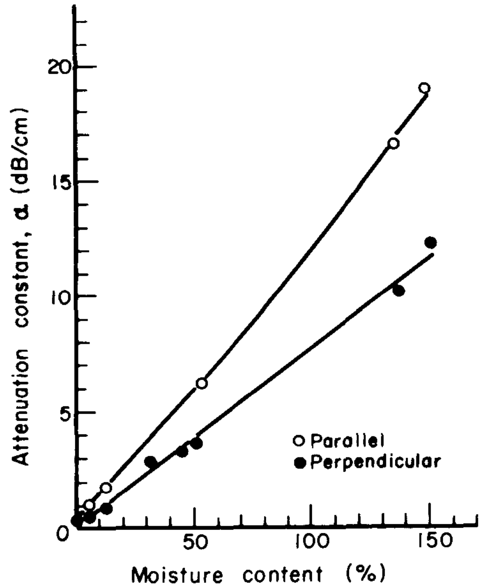

Figure 2.—Attenuation constant of Douglas-fir parallel and perpendicular to the grain as a function of moisture content. (ML84 5827)

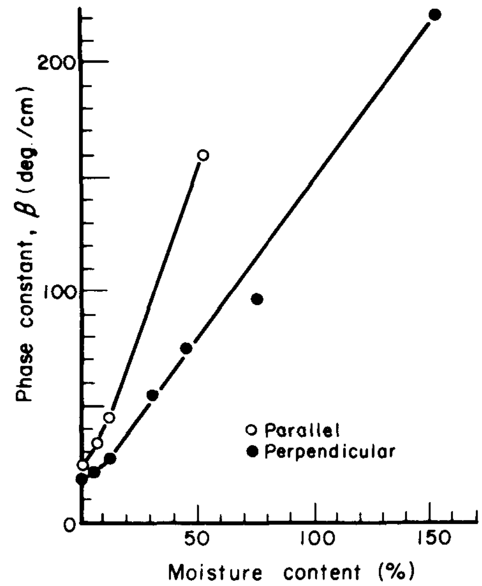

Figure 3.—Phase constant of Douglas-fir parallel and perpendicular to the grain as a function of moisture content. (ML84 5828)

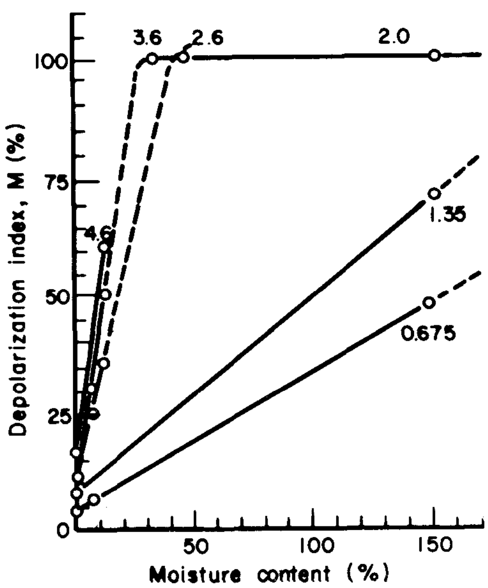

Figure 4.—Depolarization index of Douglas-fir as a function of specimen thickness and moisture content. The numbers at each curly are the corresponding specimen thicknesses in centimeters. (ML84 5829)

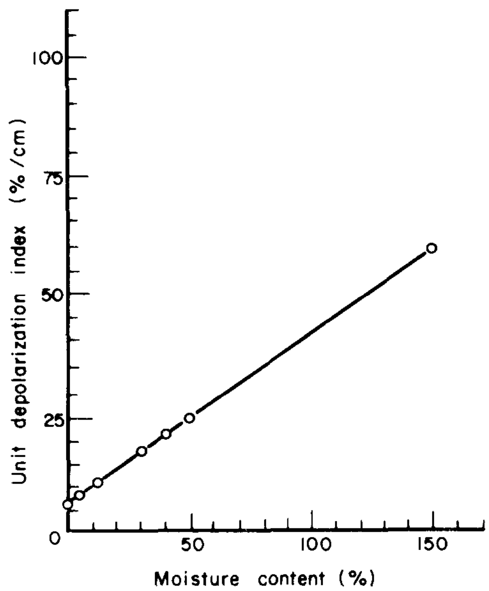

Figure 5.—Depolarization index per centimeter thickness of Douglas-fir as a function of moisture content. (ML84 5832)

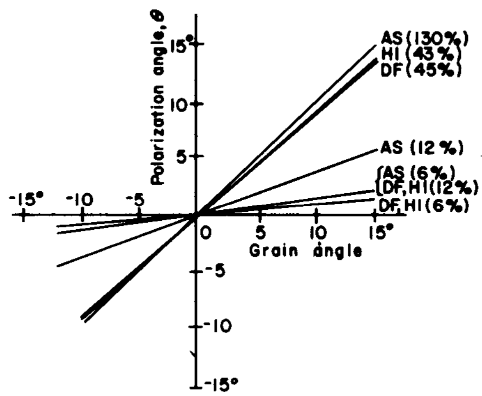

Figure 6.—Relation between polarization angle and grain angle for various species at various moisture content, for l-inch thickness. The slopes of these plots are the depolarization index, M, expressed in percent. WP = white pine, BS = basswood, AS = aspen, DF = Douglas-fir, RO = red oak, HI = hickory. Numbers in parentheses are moisture content. (ML84 5833)

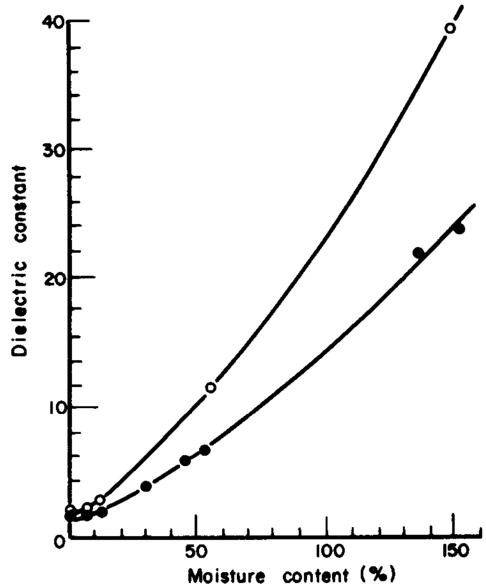

Figure 7.—Dielectric constant of Douglas-fir parallel and perpendicular to the grain as a function of moisture content. (ML84 5830)

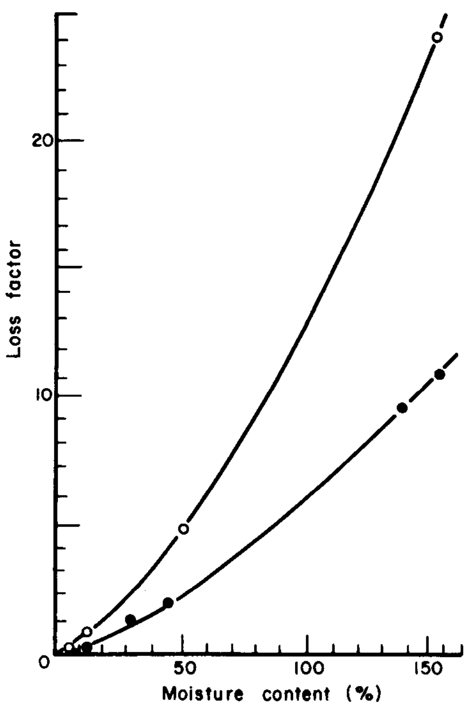

Figure 8.—Loss factor of Douglas-jr parallel and perpendicular to the grain as a function of moisture content. (ML84 5831)

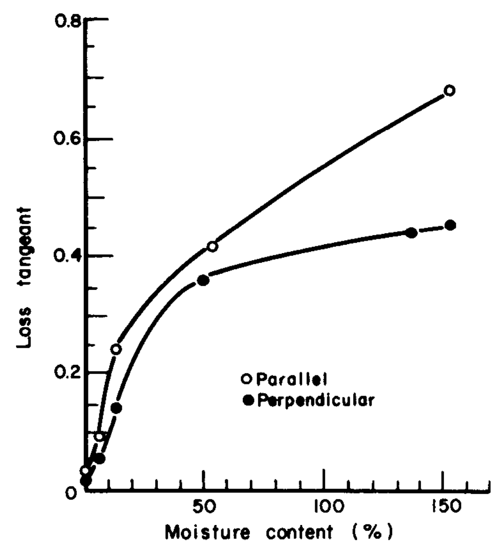

Figure 9.—Loss tangent of Douglas-fir parallel and perpendicular to the grain as a function of moisture content. (ML84 5834)

Summary and Conclusions

The research reported here demonstrates that a microwave transmission method, working at about 4.81 GHz and incorporating simultaneous amplitude and phase modulation of the transmitted wave as it is reflected back to the transmitter, can provide an accurate estimate of the dielectric tensor of the transmitting medium. With wood, the elements of the dielectric tensor, the polarization angle, and empirical calibration data can be used to infer the density, MC, and grain angle of the specimen. The correlations appear to be useful over a range of MC greater than 100 percent. The computations are complicated, but a typical small computer can provide the above quality parameters of the wood in real time (practically instantaneously).

The apparatus is also relatively complicated, but consists of components that are commercially available or easily made in a typical machine shop. The cost of none of the components is prohibitive; the complete system would probably cost about as much as a present-day production-line moisture meter. The power level of the microwave beam is typically less than one watt, so poses no environmental hazard.

This research shows that the microwave system described is potentially capable of providing production-line inspection of structural lumber, by recording density, MC, and grain direction of the material in real time. The size and physical layout of the equipment would not be a problem in typical lumber mills, and the computer software for reducing the microwave data to the desired quality parameters of the wood would be easily developed based on the results of this research (King and Yen 1981; Yen 1981). Equipment for marking the individual boards according to the computer output is available.

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Early research at the Laboratory helped establish U.S. industries that produce pulp and paper, lumber, structural beams, plywood, particleboard and wood furniture, and other wood products. Studies now in progress provide a basis for more effective management and use of our timber resource by answering critical questions on its basic characteristics and on its conversion for use in a variety of consumer applications.

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