NEAR-FIELD MILLIMETER-WAVE IMAGING OF NONMETALLIC MATERIALS*

by

N. Gopalsami, S. Bakhtiari, and A. C. Raptis

Energy Technology Division
Argonne National Laboratory
Argonne, Illinois 60439

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Gopalsami N., Bakhtiari S. and Raptis A. C.
Energy Technology Division, Building 308
Argonne National Laboratory
Argonne, IL 60439, USA

ABSTRACT

A near-field millimeter-wave (mm-wave) imaging system has been designed and built in the 94-GHz range for on-line inspection of nonmetallic (dielectric) materials. The imaging system consists of a transceiver block coupled to an antenna that scans the material to be imaged; a reflector plate is placed behind the material. A quadrature IF mixer in the transceiver block enables measurement of in-phase and quadrature-phase components of reflected signals with respect to the transmitted signal. All transceiver components, with the exception of the Gunn-diode oscillator and antenna, were fabricated in uniform blocks and integrated and packaged into a compact unit (12.7 x 10.2 x 2.5 cm). The objective of this work is to test the applicability of a near-field compact mm-wave sensor for on-line inspection of sheetlike materials such as paper, fabrics, and plastics. This paper presents initial near-field mm-wave images of paper and fabric samples containing known artifacts.

INTRODUCTION

Millimeter-wave sensing and imaging has great potential for nondestructive evaluation of nonmetallic materials, particularly for on-line applications such as quality control of materials in the paper, textile, and plastic industries. The fact that the mm-wave technique can be coupled into materials remotely (i.e., without contact) is attractive to industries. Because in many practical situations only limited access (often from one side) is available for inspection of process materials, another attractive feature is the use of a monostatic mm-wave sensor in which both the transmitter and receiver are positioned on the same side of the material. The transmitter and receiver components can be compact when higher mm-wave frequencies are used, and they can be built economically with solid-state devices and mass production techniques.

The reflection and transmission of mm waves in a material are dependent on the material's dielectric property, which is characterized by the complex dielectric constant $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$. By measuring the amplitude and phase values of reflected or through-transmitted signals, we can accurately determine the spatial variations in dielectric properties of materials, and in turn these variations can be related to changes in material properties such as density, homogeneity, thickness, and structural defects. Additionally, polarization-dependent wave propagation properties can be utilized to determine defect orientations.

The efficacy of microwave and mm-wave imaging for NDE applications has been shown in the past in low-frequency mm-wave bands [1-3]. Recently, a high-resolution mm-wave imaging system has been built in the W band (75-110 GHz) and can provide both amplitude and phase information [4]. The antenna in this system consists of a pair of spot-focusing lenses with an aperture of 0.3 m, and test samples are imaged in the focal plane of the lenses. Excellent images have been produced of delaminations, debonds, and other subsurface defects in Kevlar/epoxy composite samples. However, the size of the lenses makes the system impractical for field applications. This paper describes the design and development of a compact mm-wave imaging system for on-line applications.

DESCRIPTION OF SYSTEM

Figure 1 shows schematically the mm-wave reflection measurement system developed for on-line inspection of sheetlike materials. A bias-controlled Gunn-diode oscillator (GDO) is used as the continuous wave source at a fixed frequency (tunable at about 94 GHz with bias voltage). A built-in heater unit is used for frequency stabilization. A power divider (PD) splits the mm-wave power into two paths, one to an antenna for transmission into the material to be inspected and the other to the reference arm of a quadrature IF mixer (QIFM). Typically, a reflector (metal) plate is used behind the material to be inspected, for enhanced sensitivity. The same antenna is used to receive the reflected signal; a circulator is used to divert the return signal to the RF arm of the QFIM. Based on the reference (local oscillator) and RF signals, the quadrature IF mixer provides DC level outputs proportional to the cosine (in-phase) and sine (quadrature phase) of the phase angle between the two signals. Isolators are used in the GDO, as well as in the reference and RF arms to reduce unwanted reflections that can affect system performance. All of the components except the GDO and antenna were made in uniform sizes and packaged into a compact block measuring 12.7 x 10.2 x 2.5 cm. A scenario for on-line application is that the material moves in one direction and the sensor scans in the cross direction, thus creating an on-line image.

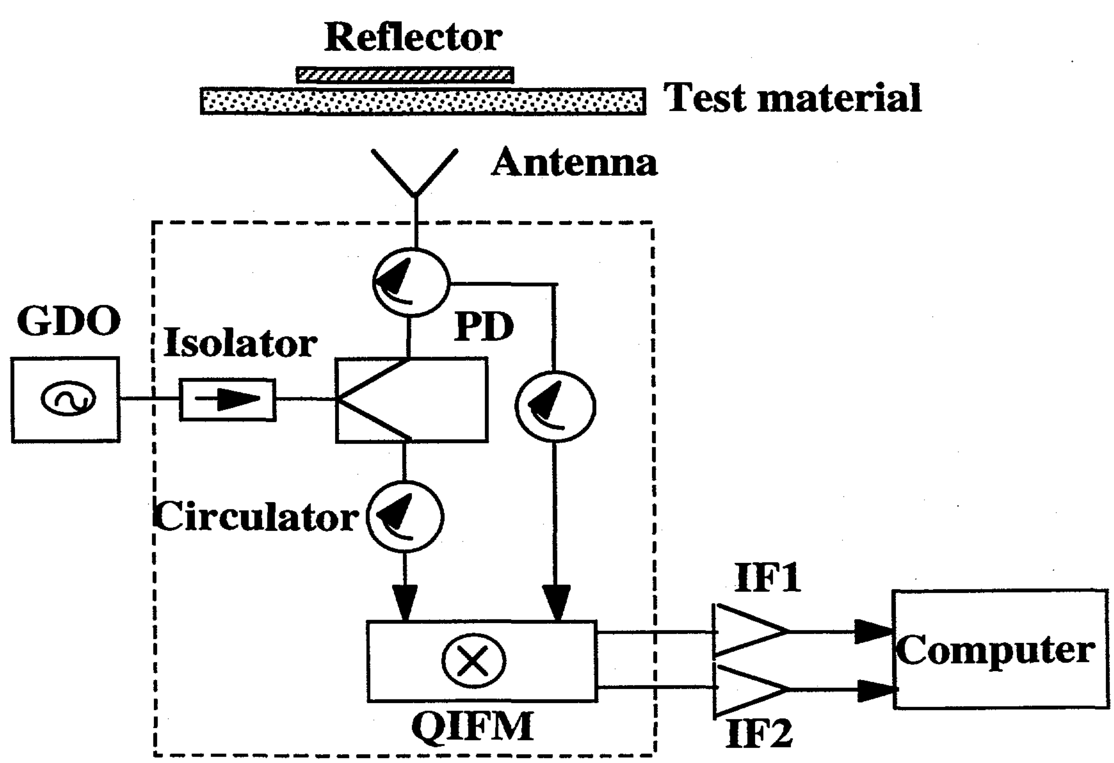

Fig. 1 Millimeter-wave reflection measurement sensor

A major challenge in adapting the mm-wave system for on-line application is the size of antenna. Although a far-field sensor is preferable from the standpoint of efficient wave propagation, signal interpretation, and insensitivity to relative position of material with respect to the sensor, it requires large-aperture antennas to achieve good spatial resolution. The use of large antennas is generally inconvenient and impractical in most situations. Small-aperture antennas such as corrugated scalar horns and open-ended waveguides can be used in the near-field mode without affecting spatial resolution. In this work, we used a corrugated horn antenna of 10 mm aperture diameter. The relative position of the antenna and material must be controlled while

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scanning to avoid baseline variation of the signals. Depending on the frequency content of the flaw signal, it is possible to minimize the baseline variation by high-pass filtering.

RESULTS AND DISCUSSION

The feasibility of the near-field mm-wave sensor was tested by obtaining images of paper and fabric samples with a two-axis translation stage in the laboratory. Two drops, one of water and the other of lubricating oil, were placed on a sheet of paper. With a reflector plate behind, the paper sample was imaged with the sensor. Figure 2 shows the amplitude and phase images of the sample. Because of the large difference in the dielectric constants of water and oil, the amplitude image shows the water spot very well while the oily spot is masked in the background. As expected, both spots are clearly visible in the phase images.

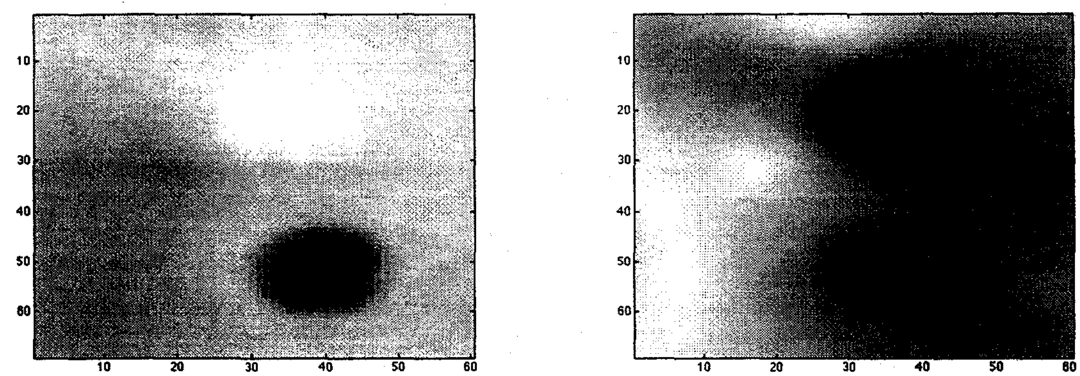

Fig. 2 Amplitude image (left) and phase image (right) of an oily spot (top) and water spot (bottom) on a sheet of paper

In another example, a fabric sample contaminated with a large patch of machine oil during weaving was imaged the same way as the paper sample. The oil had dried at the time of imaging but the spot was visible to the eye. Figure 3 shows the amplitude image of the fabric with the contaminated area clearly seen. The mm-wave image of the contaminated spot agreed well with the visual image.

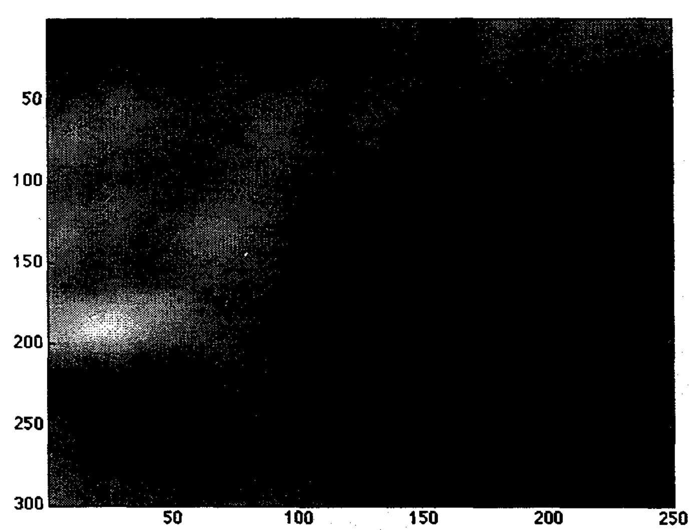

Fig. 3 Amplitude image of fabric sample contaminated with machine oil during weaving

The initial results with the paper and plastic samples show the feasibility of the near-field mm-wave sensor for nondestructive inspection of sheetlike materials. Further feasibility must be shown in an industrial process to demonstrate on-line inspection capability. With the advent of fast digital signal processors, automated imaging and defect detection can be carried out in real time for process control application.

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