NDT&E International 81 (2016) 28–38

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Design fabrication and evaluation of miniaturized passive and conformal screen printed electric field sensor for microwave Nondestructive Testing

Kayatri Kalyanasundaram, Kavitha Arunachalam *

Department of Engineering Design, Indian Institute of Technology Madras, Chennai, Tamil Nadu 600036, India

ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form
23 February 2016
Accepted 24 March 2016
Available online 26 March 2016

Keywords:
Electric field sensor
Screen printing
Carbon ink,
Microwave
NDT

ABSTRACT

A miniature conformal sensor for real time electric field measurement is proposed for microwave Nondestructive Testing (NDT). The sensor is an electrically short strip dipole antenna connected to a high speed Schottky diode through a high impedance parallel wire transmission line. Screen printable resistive carbon ink for the sensor transmission is formulated by dispersing fine graphite powder in colorless synthetic resin. The sheet resistivity measurement of the screen printed films was measured to select an ink formulation for sensor fabrication. The influence of strip dipole dimensions namely, half length (h) and width (w), and transmission line resistance (rs) on the sensor voltage was studied at low power levels (up to 3 W) using a square slot antenna at 915 MHz. Sensor measurements in the antenna near field were validated with 3D numerical simulations for a single sensor and 2×2 sensor array with sensor spacing ($\Delta/\lambda = 0.076$). The perturbation in the electric field caused by the phantom defects namely, air void, material wear and broken metal rod embedded in a 6.35 mm thick acrylic slabs was measured using a miniature screen printed sensor. Carbon ink with resin:graphite ratio of 70:30 percentage by weight was used to screen print the sensor transmission line with 0.9 MΩ/m line resistance on a 125 µm thick flexible polyethylene film. The sensitivity of the linearly polarized miniaturized sensor ($h = 6$ mm, $w = 2$ mm, $h/\lambda = 1.83 \times 10^{-2}$) at 915 MHz was measured as 31.22 mV/(V/m). Good agreement between the measurements and simulations for the phantom defects indicate that an array of miniature conformal electric field sensors embedded in dielectric composites could be effectively used for in-situ monitoring in microwave NDT.

1. Introduction

Electromagnetic (EM) NonDestructive Evaluation (NDE) is one of the widely used inspection techniques to detect flaws, cracks, corrosion and fatigue in metallic structures. The most commonly used EM techniques include eddy current testing, magnetic flux leakage and magnetic particle inspection operating in the low frequency range (1 kHz–1 MHz) of the EM spectrum. Though Microwave NDE (MNDE) over 300 MHz–300 GHz frequency range is reported for the inspection of metallic and non-metallic materials [1–4], its applications are mostly limited to industrial process monitoring [5], inspection of civil structures and earth exploration [6–9]. With the increasing use of reinforced plastics and engineered dielectrics, MNDE is emerging as a promising inspection technique for multi-layered composites where conventional eddy current and ultrasound inspection has limited use [10]. Since transient measurements involve higher data acquisition rate and processing speed, MNDE often involves free space frequency domain measurement of the wave reflection and/or transmission coefficients from bi-static or mono-static antennas connected to a Vector Network Analyzer (VNA) or, a Voltage Standing Wave Ratio (VSWR) meter [10,11]. EM field scattering in the far field defined for $\boldsymbol{kr} \gg 1$, i.e., $\boldsymbol{r} \gg \lambda/2\pi$, can be simplified using closed form equations [12], where $\boldsymbol{r}$ is the distance of the Material Under Test (MUT) from the radiation source, $\boldsymbol{k} = 2\pi/\lambda$ is the wave number and λ is the wave length of the EM field. However, the local field perturbation maintained by weak discontinuities/degradations in the MUT decay as $1/\boldsymbol{r}^3$ and can be recorded only if measurements are carried out in the reactive near field of the MUT, i.e., $\boldsymbol{kr} \ll 1$. The conventional open ended waveguide technique proposed for near field material inspection is rigid and does not conform to contoured structures [13]. As the waveguide broad wall is comparable to half-wavelength at the inspection frequency, near field material inspection is typically carried out at frequencies 8 GHz

* Corresponding author.
E-mail addresses: k.kayatri@gmail.com (K. Kalyanasundaram), akavitha@iitm.ac.in (K. Arunachalam).

http://dx.doi.org/10.1016/j.ndteint.2016.03.007
0963-8695/

and higher. Also, the diode detector requires a biasing circuit to modulate the outgoing and scattered EM fields and is placed on the waveguide aperture [13]. At the lower microwave frequencies namely 434 MHz, 915 MHz and 2450 MHz meant for Industrial, Scientific and Medical (ISM) applications, the waveguide size is relatively larger hence, the technique is of little use. Except for ground penetrating radar (GPR) [14] and industrial microwave heating [15] meant for deeper penetration, material inspection at the ISM frequencies is not widely practiced in the industry.

Unlike the active sensing elements in the near field waveguide technique, electric field distribution in the near field of the MUT could also be acquired using an electrically short non-resonant array of antennas with very low radiation resistance and broad operating frequency. Non-resonant antennas are commonly used for EM Interference (EMI) and EM compatibility (EMC) testing, radiation characterization of consumer electronics, occupational health hazard assessment and field strength measurement in telecommunication industry [16–18]. Spatially distributed monopole or dipole wire antennas are the widely used receiver designs in commercial 3D electric field probes meant for electric field measurement in space. A non-perturbing transmission line consisting of a pair of resistive wires [19], carbon impregnated tapes [20], metallic thin films [21] and optical fiber [22] have been proposed in the literature to measure the rectified low frequency signal. In this work, we present a screen printable carbon ink formulation with very high impedance for the sensor transmission line and a conformal strip dipole for real time electric field measurement from 100 MHz to 1000 MHz covering two ISM frequency bands for material inspection [23]. The proposed electric field sensor is distributed on the surface of the MUT and not on or near the source. The emphasis of this work is on capturing the local field perturbations on the MUT using passive miniature conformal electric field sensors. Thus, the MUT could be placed either in the near or far field of the radiation source.

The organization of the paper is as follows: The operation of an electrically short dipole antenna as an electric field sensor and the sensor working principle are presented in Section 2. Section 3 covers the formulation and characterization of the screen printable carbon inks, design and characterization of the screen printed sensor, 3D numerical model for sensor validation, and experimental verification on thin dielectric slabs. Sensor fabrication and characterization results and experimental validation with 3D numerical simulations are presented in Section 4. A discussion of the results is in Section 4 followed by conclusion.

2. Sensor operation

2.1. Miniaturized electric field sensor

Fig. 1 shows an illustration of the electrically short center fed strip dipole antenna proposed for localized electric field measurement. At the operating frequency, the sensor dimensions (h, w, t) are relatively smaller compared to the wavelength, λ. The electrically short ($h/\lambda \ll 1$) center fed dipole with dipole half length, h, conductor width, $w < h$ and thickness, $t \ll w$ provides a low profile and conformal design for engineered structures with flat and curved geometries. The receiving characteristic of the dipole antenna in terms of its geometry and polarization is defined using the vector effective length, $\vec{h}_e$ [12]. Let a continuous wave, $\vec{E}^i(\vec{r},\omega)$ be incident on the z-directed electrically short strip dipole, where ω is the angular frequency in radians, and $\vec{r}$ is the position vector. The voltage induced across the open ended terminals of the short dipole is given in terms of the effective vector length as, $V_{oc} = \vec{h}_e \cdot \vec{E}^i(\vec{r}, \omega)$, evaluated at the origin, $\vec{r}=\vec{r}_0$, where $\vec{h}_e=\hat{z}h$ [12].

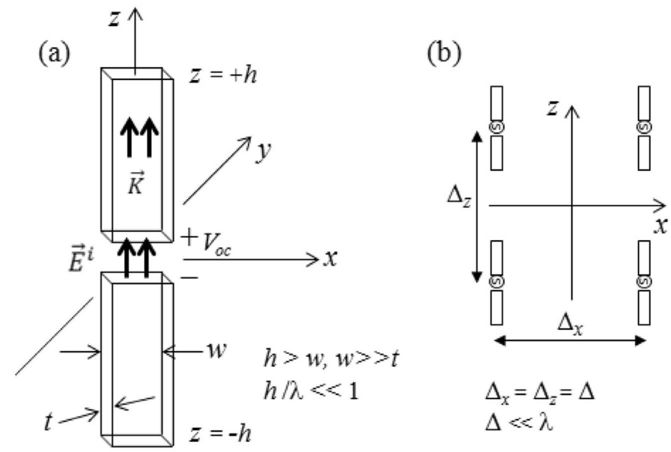

Fig. 1. An illustration of the miniaturized electric field sensor. (a) An electrically small center fed strip dipole antenna illuminated by an incident electric field, $\vec{E}^i$, and (b) 2D uniform sensor array for spatial electric field mapping. Note: Transverse electric field distribution can be measured by rotating the array or using an array of small circular loop antennas.

For an electrically short dipole sensor placed in the far field of the source, the incident field is a plane wave given by, $\vec{E}^i(\vec{r}_0,\omega)=\vec{E}_0 e^{-j(\vec{k}\cdot\vec{r}_0-\omega t)}$, where t is the observation time. If the short dipole sensor is in the near field of the radiating source, the incident electric field is given by, $-j/\omega\mu_0\varepsilon_0 \nabla \times \vec{B}$, where μ_0 is the free space magnetic permeability, ε_0 is the free space dielectric permittivity and $\vec{B}$ is the magnetic field strength given by $\vec{B}=\nabla\times\vec{A}$ which is related to the induced current density, $\hat{z}K$ on the dipole arms and the free space Greens function, G by the convolution operation, $\vec{A}=\hat{z}(K*G)$ [12]. For an electrically short dipole, the spatial variation of the incident electric field along the dipole length is negligibly small thus, $\vec{K}=\hat{z}I\Pi(z)$, where I is the induced current amplitude, $\Pi(z)$ is a unit pulse function defined over $-h \le z \le h$, and the open circuit voltage, V_{oc} can be approximated as, $hE^i_z(0,\omega)$ [18,24]. The voltage drop across the gap between the conducting strips of the electrically short dipole antenna results in a capacitive impedance, $Z_A= -j/\omega C_A$ with $C_A=\pi\varepsilon_0 h/[\ln(h/a)-1]$, where $a = w/4$ is the equivalent radius of a circular dipole antenna [18,24]. Based on the theory, an electrically short dipole must satisfy the criteria of $h/\lambda \ll 1$, $w<h$ and $t \ll w$ for local measurement of the incident electric field. Furthermore, due to the very low radiation resistance typically of the order of few Ohms [25], the open circuit voltage of an electrically short dipole gives a measure of the local electric field strength with minimal perturbation to the incident EM field. Different array configurations could be realized using horizontal, vertical or circularly polarized non-resonant antenna elements to yield high density measurement of the electric field strength in space. Fig. 1b shows the two dimensional (2D) uniform array of electrically short dipole receivers proposed for real time spatial mapping of the electric field strength.

2.2. Electric field measurement

Fig. 2a shows the schematic diagram of the miniaturized electric field sensor constructed in this work. The sensor consists of an electrically short strip dipole antenna connected to a diode detector and a high impedance parallel wire transmission line terminated by a load resistor. A Radio Frequency (RF) Schottky diode detector with high switching speed and good sensitivity was selected to rectify the incident time harmonic electric field. The resistive two wire transmission line of length, s minimized the perturbation of the incident EM field and prevented stray EM field