DEVELOPMENT OF 'LICK AND STICK' PASSIVE WIRELESS TEMPERATURE SENSOR FOR HARSH ENVIRONMENT

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Dedication

My mother Mosammat Begum Nurjahan, my father Ali Karim, my brother Nazmul Karim, & my wife Naznin Jahan Afrose

DEVELOPMENT OF 'LICK AND STICK' PASSIVE WIRELESS TEMPERATURE SENSOR FOR HARSH ENVIRONMENT

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Abstract

Wireless passive temperature sensors have been receiving increasing attention due to the ever-growing need of higher energy efficient and precise monitoring of temperatures in high temperature energy conversion systems such as gas turbines and coal-based power plants. Unfortunately, the harsh environment such as high temperature and corrosive atmosphere present in these systems has significantly limited the reliability and increased the cost of current solutions. Therefore, this research project presents the concept and design of a low cost, passive, and wireless temperature sensor that can withstand high temperature and harsh environment. The temperature sensor was designed following the principle of metamaterials by utilizing Closed Ring Resonators (CRR) in a dielectric matrix. The proposed wireless, passive temperature sensor behaves like an LC circuit, which has a temperature dependent resonance frequency. A full wave electromagnetic solver Ansys Ansoft HFSS was used to validate the model and to evaluate the effect of different geometry and combination of SRR structures on the resonance frequency and sensitivity of the proposed sensor. Two different fabrication methods – compression method using a die-punch assembly and 3D printing using binder-jetting techniques were used to fabricate the sensors. To simplify the sensor design, commercially available metal washers were used as CRR structures. Barium Titanate (BTO), and Alumina (Al_2O_3) were used as dielectric materials. Material characterization was done using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD), and preliminary free space testing at room temperature using horn antennas and Gaussian beam antennas very promising results for using this novel sensing system for harsh environment application.

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Chapter 1: Introduction

There is an increasing demand for the further development of sensing technologies in the energy conversion systems such as gas turbines, coal based power plants, and in automotive industries. Precise temperature sensing is one of the most critical parameters to safeguard better combustion, achieve higher efficiency and lower contaminant emissions to the environment. Since these combustion processes create a harsh environment of high temperature and corrosive conditions, it is imperative that the sensors are made to survive this environment and at the same time being reliable. Eventually, necessity of wireless sensors increased as the wired systems are found to be expensive, complicated, and they limit the operating temperatures. Previous efforts on the regime of wireless sensing include thermocouples, thermoelectric materials and fiber optics. However, most of the approach is limited due to either being complicated or expensive. Furthermore, low reliability has been identified as an issue while working on harsh environments due to the use of welded joints, energy storage devices, and semi-conductor materials in their arrangements [1-3]. Therefore, there is an ever-increasing interest in developing passive, wireless, low cost and reliable temperature sensors capable of working in the hostile environments present in energy conversion systems. This thesis is a proposal for a passive wireless temperature sensor for harsh environments inspired from the concept of metamaterials. This first chapter of the dissertation presents the background of the study, describes its significance, and provides an overview of the methodology used.

1.1 Introduction to metamaterials

Meta is a Greek word, which means “beyond”, hence the word “metamaterials” refers to materials that can display properties that are beyond the properties of natural materials. Usually the structure of these materials plays a significant role deciding its properties rather than the material properties of its components. When an electromagnetic wave passes through a material, the otherwise nonhomogeneous medium can be considered as a homogeneous medium if the

atoms of that material are very small compared to the wavelength of the incident electromagnetic wave. So, from the electromagnetic point of view, it is the wavelength λ that determines whether a collection of objects can be considered as a material or not. The block of objects might not be considered as a material by the conventional definition of materials but to the incident electromagnetic wave there is no difference and hence this can be considered as an artificial material or metamaterial [4]. Such homogeneous medium can be characterized by only two parameters: electric permittivity (ε) and magnetic permeability (μ). These two parameters are very important and determine the propagation characteristic of an electromagnetic wave through a medium, which can be shown by the dispersion equation. The dispersion relation for an isotropic medium is defined as:

$$k^2 - \frac{\omega^2}{c^2} n^2 = 0 \tag{1.1}$$

Where, k is the wavenumber, ω is the angular frequency, c is the velocity of light in vacuum and n is the refractive index of the substance, which is given by,

$$n = \sqrt{\mu_r \epsilon_r} \tag{1.2}$$

Where, μ_r is the relative permeability and ε_r is the relative permittivity of the medium. For most of the natural materials both relative permeability and permittivity are positive and hence n is also a positive number. As long as both μ_r and ε_r have the same sign, n is a real number and wave will propagate through the medium but, if one of them is negative then n becomes imaginary and there will be no transmission for a thick substance. Now, the significance of both negative ε_r and μ_r can be further investigated by examining Faraday's and Ampere's law. For a monochromatic plane wave that uses $e^{j\omega t}$convention, Ampere's and Faraday's law are expressed in equation 1.3 and 1.4 respectively:

$$\vec{k} \times \vec{H} = -\omega \varepsilon \vec{E} \tag{1.3}$$

$$\vec{k} \times \vec{E} = \omega \mu \vec{H} \tag{1.4}$$

Where, $\vec{k}$ is the wave vector, $\vec{H}$ and $\vec{E}$ are magnetic and electric field intensity vectors respectively. When both ε and μ are positive, from equation (1.3) and (1.4) it can be seen that $\vec{k}$, $\vec{H}$ and $\vec{E}$ form a right-handed co-ordinate system whereas when they are both negative, the

vectors form a left-handed co-ordinate system. A comparison between left-handed and right-handed co-ordinates systems is shown in Figure 1.1. Veselago's proposal of an artificial medium that can have simultaneously negative values of permittivity (ε) and permeability (μ) in 1968 was actually the starting point of the research on

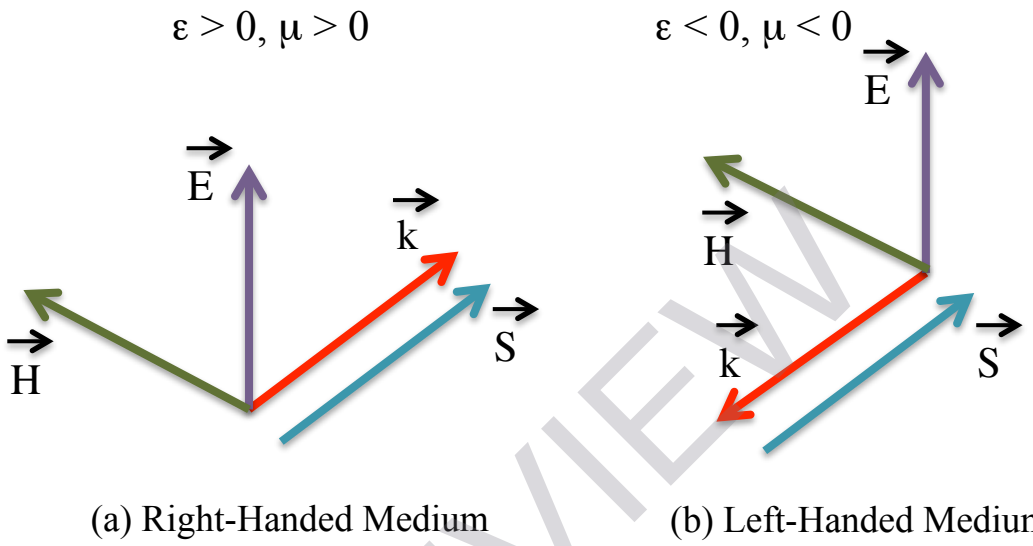

Figure 1.1: Directions of the Electric (E) and Magnetic (H) vector fields, wave vector (k) and the power flow density (S) vector in (a) Right Handed Medium and (b) Left Handed Medium

left-handed metamaterials [5]. It was expected that a left-handed medium would display some nonconventional behaviors such as backward propagation, reverse Doppler effect, reverse Vavilov-Cerenkov effect, and negative index of refraction [6]. The phenomenon of negative index of refraction can be explained with a modified Snell's law. When a ray of light passes from one medium to another medium the refraction of the light follows the general Snell's law (equation 1.5) if both media are right handed. As shown in Figure 1.2, the incident light ray is reflected along path 2 and refracted through path 3. However, if one of the media is left handed then a more accurate form of the Snell's law is used (equation 1.6). In that case, the refracted light goes along path 4.

$$\frac{\sin\theta}{\sin\phi} = \frac{n_2}{n_1} = \sqrt{\frac{\mu_2\varepsilon_2}{\mu_1\varepsilon_1}} \tag{1.5}$$

$$\frac{\sin\theta}{\sin\phi} = \frac{n_2}{n_1} = \frac{p_2}{p_1}\left|\sqrt{\frac{\mu_2\varepsilon_2}{\mu_1\varepsilon_1}}\right| \tag{1.6}$$

Where p_1 and p_2 are the rightness of the first and second medium respectively. p is +1 for a right handed medium and it is -1 for a left handed medium.

Negative values of permeability and permittivity can be obtained by combining special resonator structures with appropriate excitation techniques. There are three types of excitations that can be used for metamaterial resonator structures. They are: magnetic excitation, electric excitation and both magnetic and electrical excitation [6-8]. The choice of the excitation depends on the desired application. If ENG regions are required, the structure has to be excited electrically and it has to be excited

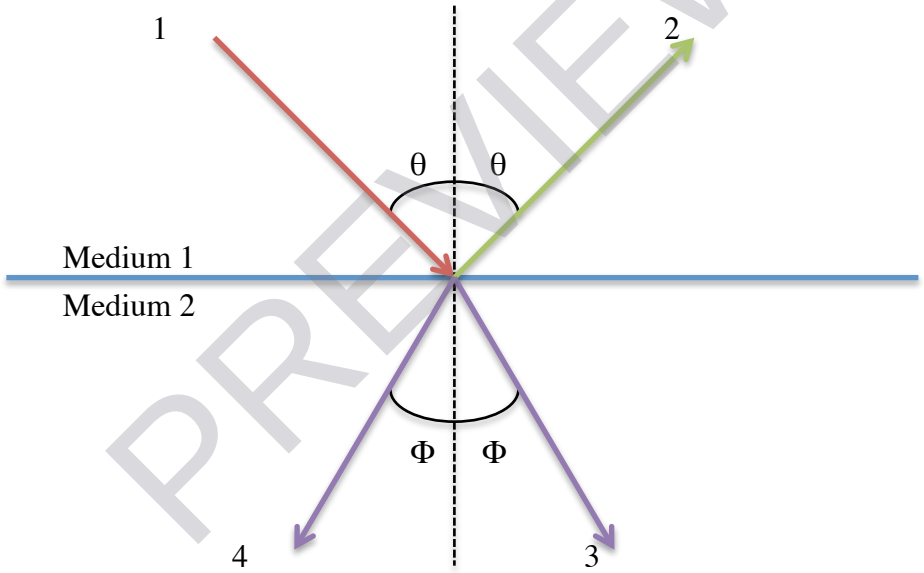

Figure 1.2: Light ray passing from medium 1 to medium 2. 1) incident ray, 2) Reflected ray, 3) refracted ray in a right handed medium and 4) refracted ray in a left handed medium

magnetically in order to obtain MNG regions [8]. Figure 1.3 summarizes the excitation techniques for a SRR structure. In figures 1.3(a) and 1.3(b), the magnetic field is perpendicular to the SRR plane. Hence, according to the Faraday's law of induction it can excite the magnetic resonances of the SRR. On the other hand when the magnetic field is parallel to the SRR plane it cannot excite a magnetic resonance. In figures 1.3(b) and 1.3(c), the electric field is

perpendicular to the gap of the rings. This configuration can excite the electrical resonances of the structure. Hence, the structure in figure 1.3(b) is excited both electrically and magnetically and the structure at 1.3(d) is not excited at all from the sense of an LC circuit.

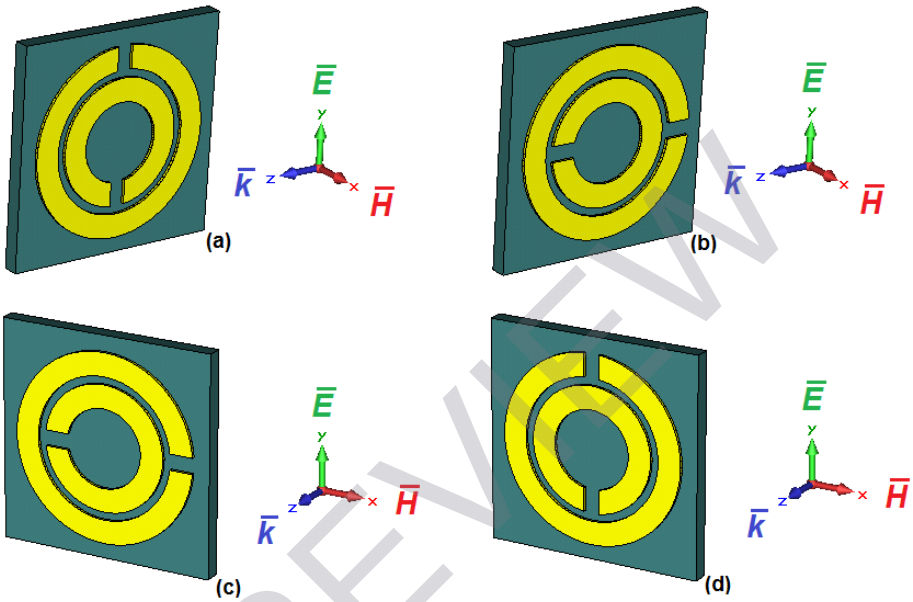

Figure 1.3: Different excitation techniques for SRR structure (a) only magnetic excitation (b) electric and magnetic excitation (c) only electric excitation and (d) no excitation. [9]

Prior to the development of metamaterials, materials with single negative index were found in nature, which were either Epsilon Negative media (ENG) or Mu Negative media (MNG). The concept of a Double Negative media (DNG) or Left Handed Media (LHM) was exciting, but it was not realized in reality until in 1999 when J.B. Pendry et al. [10] proposed the use of periodical arrays of SRRs (Split Ring Resonators) and thin-wires together where the negative values of effective permeability are obtained from the SRR structure and the negative values of permittivity are obtained from the thin wire array. It has been demonstrated that metamaterials need to appear as an effectively homogeneous media, which means that their lattice constants have to be smaller than the wavelength of the incident radiation [11].