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Contactless load monitoring in near-field with surface localized spoof plasmons—A new breed of metamaterials for health of engineering structures

Venu Gopal Madhav Annamdas*, Chee Kiong Soh

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore

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ABSTRACT

In the recent past, the structural health monitoring (SHM) using various smart materials are in demand due to several reasons. These include (i) continuous increase in construction/manufacturing activity, (ii) demand in lifespan increase of the existing engineering structures, and (iii) never ending thrive to modernize existing/traditional SHM technologies. However, there are several existing issues of smart materials, such as sensor size, signal inaccuracies, low noise to signal ratios and sensitivity limitations that need improvement. Hence, a continuous thrive exists for newer materials and their suitability to improve SHM technologies for engineering. The arrival of electromagnetic (EM) radiation based metamaterials has raised the curiosity due to its rapid measuring speeds, sensitivity, and remote sensing ability. Metamaterial designs are applied often in physics and the sciences but are seldom in engineering. In this paper, an ultra-sensitive contactless monitoring technique which comprises of near-field intensity measurement of surface EM waves in a special patch known as surface localized spoof plasmon (LSP) structure is presented. The principle involves the EM wave application in the radio frequency range that can be extremely localized at the interface of a metal and the dielectric medium (air) of the LSP structure. This EM intensity decays exponentially away from the interface, resulting in the nonlinear response to deformation, suitable for the health inspection of engineering structures. Its suitability for load monitoring in the transverse direction of an engineering beam is verified for two different boundary conditions by a root mean square deviation (RMSD) index.

1. Introduction

Structural health monitoring (SHM) plays a key role to evaluate the performance and integrity of engineering structures such as buildings, bridges, machines and airplanes [1]. The worldwide increase in demand for traditional and smart material based SHM is due to several reasons. These include (i) continuous increase in construction/manufacturing activity, (ii) demand in life expectancy increments of the current engineering structures, and (iii) never ending thrive to modernize existing/traditional SHM technologies by adding features such as automation and efficiency. In the recent years, smart material based SHM is on the rise, especially using fiber optical sensors (FOSs) [2,3] and piezoelectric sensors (PZTs) [4,5] due to their several advantages over the traditional monitoring technologies [6–8]. Over the years, there was a tremendous improvement in all these technologies that greatly reduced manual intervention [9] to a great extent by wireless integration [6] and smart signal/signature processing [10] using advanced software-hardware technologies. However, there are many challenges to be addressed such as the sensor size, bonding problems with engineering structure leading to strain lag, interferences in structural functionalities, output signal inaccuracies, low noise to signal ratios, sensitivity limitations and the excessive collection of unnecessary noise [4,5,9]. Hence, a continuous thrive exists for newer materials and their suitability to improve SHM technologies.

The arrival of electromagnetic (EM) radiation based metamaterials [11] has raised the curiosity due to its measuring speeds, wireless sensing and sensitivity, which has future potential of application in engineering without interfering with day-to-day duties of structures if properly realized. In the recent past, several metamaterial inspired sensors and their breeds with different structural designs are rising [12–15]. Some breeds and their structural designs such as split ring resonators (SRRs), surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs) samples [11,16–20]

* Corresponding author.
E-mail address: venu.iisc@pmail.ntu.edu.sg (V.G.M. Annamdas).

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were applied frequently in physics and the sciences but are seldom in aerospace, civil and mechanical (ACM) engineering.

A new sensor developed by physics or electronics group needs standardization and evaluation by ACM engineering groups if it has to spread its applications beyond the developmental stages. Moreover, sensor validation is necessary for engineering parameters such as load, deformation, strain, temperature, fatigue, crack, boundary conditions etc. before using them in actual practical engineering conditions. For example, PZT sensors [4,5,21,22] were tested for loading, damages, etc., before it was used in a real application at a Mass Rapid Transit construction in Singapore [9]. This paper explores the realization of such a metamaterial inspired sensor, known as spoof LSP sample, developed a couple of years ago by Shen and co-researcher group [13,23] which resembles a patch (Fig. 1a) similar to the PZT sensor (Fig. 1b-c) developed several decades ago. The sensor realization of the LSP is required so that it can be compared with active and passive smart materials [24] and can be employable in SHM alongside established smart materials in our future applications [5].

Thus, this paper presents a contactless ultra-sensitive monitoring technique by measuring near-field intensities of the surface EM waves in a spoof LSP sample for load monitoring along transverse (perpendicular to the surface) direction of engineering structure. The principle involved the EM wave application in the radio frequency range that can be extremely localized at the interface of a metal and the dielectric medium (air) of the LSP sample (Fig. 1d) [23,25]. This EM intensity decays exponentially away from the interface in a perpendicular (vertical) direction (Fig. 1e-f), resulting in the nonlinear response [25] that can be used for measurement of the deformation of an engineering structure [26] located at a distance away from the LSP sample as presented in this research. This denotes that the LSP sample is not in-contact with the engineering structure throughout the process of monitoring of the engineering structure.

2. Engineering applications of metamaterials

Metamaterials and subsequent breeds have been successfully tested in optical applications such as invisibility cloaking [27,28], sub-wavelength imaging [29], gradient negative index lenses [30], perfect absorbers [31], metasurface [32], photonic topological insulators [33] and so on. Their entry in SHM [26,34–37] started attracting engineers because of their strong EM response to the geometrical change of unit cells or elements of the patch [38], making it suitable as strain gauges.

In the recent past, several metamaterial based wireless strain gauges were proposed by designing sensing units based on SRRs [39,40], where the sensing units mostly need physical contact to the engineering structure and are intended only for in-plane strain monitoring. The principle involves measurement of resonance frequency shifts caused due to the geometrical variation of the resonator [37,39,41]. However, Shen and co-researchers group [13,23] successfully presented spoof LSP samples by obtaining signal characteristics such as modes, which has huge potential for engineering applications, especially for strain measurements.

However, several challenges remain to be addressed as most metamaterial or new breads are:

(1) Designed only for measurement of “in-plane” stretch/compression, and are not compatible for “out-of-plane” deformations [35,42].
(2) Physically attached (in contact) to the surface of the structure under investigation, which may interfere with the working of the structure or may become vulnerable.
(3) Mostly based on the progressive wave measurements in far fields, where signal leakages and reflections force its measurements in very expensive anechoic chambers. Even if surface waves were used in near fields, they were not “realized as sensors” for engineering applications.
(4) Never assessed for sensitivity using quantifiable statistical analysis, such as root mean square deviation (RMSD).
(5) Not yet realized as sensors especially as contactless sensors for SHM applications.

These limits their application in ACM engineering, which often need real, in-situ and online monitoring of in-plane and out-of-plane measurements for various engineering parameters.

Furthermore, no single SHM technology or single smart material or metamaterial can provide solutions to all complex engineering problems [2,5,43,44]. Thus, SHM strategists require to apply several combinations of various SHM technologies to monitor strain, temperature, crack, etc. for engineering structures such as airplanes, machine, bridges, and buildings [4,5]. Most of these SHM technologies need “physical contact” of the sensor structure with the engineering structure. Some of these sensors are glass based such as fiber bragg gratings or FOS sensors, which need careful physical packaging to protect them [45]. Some are fragile piezoceramics, such as PZT patches, which also needs protection when employed in actual practice [9].

Thus, this paper explores a novel ultra-sensitive contactless monitoring method where the sensor is not required to be in contact with the engineering structure under investigation as shown in Fig. 2a, unlike other smart SHM technologies . It presents the realization of a new sensor based on recently developed spoof LSP sample [23] by physics group whose design is based on a *meta-atom: a planar—plasmonic LSPs. The spoof LSP design employed in this study is* [23] as shown in Fig. 1(a,d) [25]. This is similar to circular PZT patch as shown in Fig. 1(b,c) [21,22], prevalent type of smart material. Earlier, these LSP samples have been explored in various applications such as photonic energy transport [46], super resolution imaging [47], cloaking [48] and wave guiding [49] but not as a sensor. However, the recent discovery of vertical transportation of surface wave energy [50] creates several possible applications including load monitoring perpendicular to the beam, where the sensitivity is a crucial factor. This sensitivity is proportional to the quality factors and they are dependent on the confinement of EM wave.

This paper thus presents the usage of surface wave generated by an LSP sample (Figs. 1e-f and 2b) with three dimensional (3D) EM wave confinements suitable for strain measurements. These generated surface wave evanescence with no need to worry about leakages and wastages. Hence, several advantages of this LSP sample made it a suitable candidate for load monitoring of engineering structure in,

1. X-Y plane: The wave intensity changes in the plane of the resonator/sensor patch (see spectrum in Fig. 1e).
2. Z- axis: This resonator can offer sub-wavelength confinement of EM wave in Z-axis, perpendicular to resonator plane. The intensity of the evanescent EM wave decays exponentially, away from the resonator in Z-axis forming a nonlinear response which is ultra-sensitive to subtle ambient deformations (Fig. 2). Thus wave intensity deteriorates in an angular direction as LSP sensor rotates (see spectrum in Fig. 1f).
3. Contactless sensing: The surface wave intensity in the resonator can be probed contactless without using an anechoic chamber in the near-field, enabling non-destructive load monitoring for engineering applications.