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Annamdas, Venu Gopal Madhav; Soh, Chee Kiong

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**Title: Application of Metamaterial Surface Plasmon and Waveguide for Robotic-arm
based Structural Health Monitoring**

Authors: Venu Gopal Madhav Annamdas* and Chee Kiong Soh

School of Civil and Environmental Engineering

Nanyang Technological University

50 Nanyang Avenue

Singapore 639798

E-mail (*Corresponding Author): annamdas@ntu.edu.sg,

Phone : (65) 84826323,

Fax: (65) 6 791-5093.

Abstract Several electromagnetic (EM) metamaterial designs and their variants, such as localized surface plasmons (LSPs), with ultra sensing capabilities for structural health monitoring (SHM) have emerged in the last few years. These LSPs, in a confined configuration with the ‘engineering structure under inspection’ generate a unique diagnosable surface plosmons/ wave as output, when subjected to input EM waves in the near fields. This paper presents a procedure to enhance the output surface wave zone by adopting them in a non-confining configurations. A novel procedure of transferring ‘surface waves’ from within the confined boundaries of LSP to far-off distance along a guided path is presented. This is achieved for both confined and non-confined configurations to monitor displacements as small as $1/100^{th}$ of a mm and as large as 10’s of cms, respectively, highlighting the wider scope for real world applications. In experiments, the input EM waves were supplied by the vector network analyser, and the output surface waves were collected by the same via a 2D robotic scanner, controlled using custom software. Metallic specimens in confined configuration such as ‘aluminium’ shell and beam were used for monitoring “angular” and “vertical” deformations. Further, non-metallic specimens in non-confined configurations such as ‘rubber’ bicycle tube and ‘concrete’ blocks were used for monitoring “pressure” and “horizontal” displacements. Flexibility of a LSP sensor allowed its easy attachment to various specimens by bending and twisting which ranged from linear (0^0) to double bent (180^0) shapes. This paper provides a window of opportunity for SHM application of bendable metamaterials using waveguides and robots.

Keywords: Electromagnetic radiation (EMR), metamaterials, localized surface plasmons (LSP), structural health monitoring (SHM), surface wave, robot, bendable

1. Introduction

Over the past couple of decades, there has been tremendous improvement in the field of structural health monitoring (SHM) that reduced human intervention to a large extent by wireless communication, integration of automation and signal processing [1 - 3]. However, there remain many challenges to be addressed for effective implementation of several complex SHM techniques. These include problems pertaining to sensitivity limitations, sensor size, scanning areas, interferences in structural functionalities, output signal inaccuracies, large human acquisitions, underused robotic implementations, and excessive collection of unnecessary data [4 - 8]. Hence, there is continuous drive for exploring newer materials and techniques for SHM. Recently, metamaterials and their variants have been presented as ‘smart’ materials with ultra sensing capabilities for monitoring several biological and engineering structures [9 – 12]. Hence, researchers especially from material sciences, physics, electronics and electrical engineering are developing new metamaterial designs which can be adoptable for aerospace, civil and mechanical (ACM) structures [13 – 18]. These newer designs need evaluation by ACM research groups based on several sensor characteristic features such as the size, shape and material properties, and their comparisons with existing SHM sensors for acceptance or rejection before their applications in ACM engineering [19]. In the recent past, electro-magnetic (EM) metamaterials, such as split – ring – resonator (SRR), surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs) were validated for several applications including a few in SHM [20 – 25]. These EM metamaterials comprise of varieties of resonators made of metal or plastic inscriptions on materials such as Rogers RT, printed circuit board (PCB). These inscriptions are assemblies of multiple elements arranged in repeating patterns of sizes/ shapes that are designed to be smaller than the wavelengths of the bandwidth of input EM waves. Their precise shape, geometry, size, orientation and arrangement give them their smart properties capable of altering EM waves by blocking, absorbing, enhancing, or bending [13,

26] and thus they can be considered as part of ‘family of smart materials’. The output in the form of either progressive or surface waves in the far or near fields, can be used for various studies, including health diagnosis of biological and engineering structures [27, 28]. Most of their applications are executed in closed anechoic chambers to avoid possible reflections that could interfere with the signals, generated by input-output devices such as a vector network analyzer (VNA), EM scanners, etc. [29 – 33]. The isolated condition of performing experiments hampers their rapid application for monitoring of ACM engineering structures, which are mostly rugged.

This article focuses on novel implementation of robotic arm for accessing assessing workability of the near-field based LSP sensor with and without waveguide in the absence of an anechoic chamber, a step towards the automation of novel LSP sensing technique for SHM applications. Moreover, in a near-field experiment, input/ output probes (antennas), required for execution are placed close to the sensor. This avoids the need for the long distance transmission of EM waves, which automatically eliminates interference of EM waves created by any adjacent LSP sensor or refractions/ reflections due to other electronic devices. In the past, similar laboratory studies were carried out for other smart materials such as piezoelectric (PE) sensors and Fiber Bragg Gratings (FBGs) sensors for about 2 decades before their execution in real-world ACM engineering applications [3, 4, 34]. Thus, this article forms the basis for future practical applications of metamaterial LSP sensor using robotics and waveguides in SHM.

1.1 LSP Sensor

Metamaterials and subsequent variants/ hybrids have been successfully tested in several non-ACM applications especially for optics viz., invisibility cloaking [13, 35], sub-wavelength imaging [36], gradient negative index lenses [37], perfect absorbers [38], metasurface [39], photonic topological insulators [40] and so on. Their entry in SHM of ACM structures [22, 29, 41-44] started attracting engineers and researchers because of their strong EM response to the

geometrical changes in the unit element or assemblies of elements [27], making it suitable for ‘strain’ monitoring, where many strain related issues are common problems for most ACM structures.

At present, no single SHM technique can provide solutions to all complex health/ ageing problems faced by ACM structures [7, 5, 45, 46]. Thus, ACM researchers opt application of several combinations of many SHM techniques to monitor strain, deformation, etc., for structures such as airplanes, machinery, bridges, and buildings [4, 5]. Most of these SHM techniques need to apply sensors in ‘contact’ and ‘contactless’ configurations with the engineering structure for signal acquisitions. At present, some of the predominant sensors are glass - FBGs that are intermittently placed along optical fiber cables which transfer EM waves to and from the FBGs. These FBG sensors and optical fiber cables are respectively, contact sensors and contact waveguides which need careful physical packaging [47] to avoid any possible breakages. There are many more such fragile smart sensors such as PE sensors used commonly in SHM. Additionally, electrical cables that supply current/ voltage to these sensors also need protection when employed in practice, which increases the overall cost and complexity of the test setup [3].

On the other hand, metamaterials such as LSP sensors are highly non-fragile which are manufactured as bi-material composites, made of metal or plastic or polymer inscriptions on flexible and ultra-thin materials such as Rogers (RT5880) using PCB technique. These are bendable and twistable that range from linear (0°) to double bend (180°) shapes. Furthermore, these LSP sensors do not require fragile packaging unlike FBG sensors and moreover their ‘waveguides that transfer EM waves’ do not need any protection unlike optical fiber cables.

If any metamaterial and their breeds have to be effective for sensing application of ACM structures, then their designs and implementation schemes need to cater to small, medium and large-scale structures. Most of the present designs [31, 48] have not been tried for ACM

engineering structures. Moreover, these materials have also been designed only for monitoring in-plane stretch/ compression during axial loading and cannot be compatible for out-of-plane deformation measurement during transverse loading [42, 49]. They are mostly based on the generation of (1) ‘progressive wave’ that travel long distances in the ‘*far fields*’ (air medium); and (2) the measurement of the scattered parameters in the far fields. Thus, EM radiation leakages and reflections are common, which forces experimentation in isolation i.e in special anechoic chambers. Thus, they were used mostly for biological or medical applications in anechoic chambers (isolation) [25]. However, these radiations are harmless in microwave range, and their applications for ACM engineering structure can be considered without any isolation. Hence, ‘*near field*’ based LSP sensor using robotic arm and waveguide technique is adopted in our study as illustrated in Figs. 1-3. This technique was evaluated for several laboratory based ACM engineering specimens as demonstrated in Figs 4-11, that shows its potential applications for SHM.

Fig 1(a) shows a sketch of LSP sensor, which is composed of periodic grooves with period of 1.256 mm and 0.628 mm air gap between neighboring strips (elements), etched on an 18 μm thick copper (ground plate) disk. This is engraved in a circular fashion (X – Y plane) on a 254 μm thick Rogers RT5880 comprising of a relative permittivity of 2.2 and loss tangent of 0.0009. It is symmetrical in the X-Y plane and offers EM leakage-free application in the near field for monitoring of ACM structures [29]. This is based on the design developed by Shen and co-researchers group [50,51]. The principle required for SHM application involves activation of LSP by a pair of dipole antennas where one is a point source dipole for input excitations and the other is a receiver dipole for output probing/ receiving. Both dipole antennas are operated by a VNA via a pair of input-output coaxial cables as shown in the figure. The coaxial cables respectively transport input EM waves and output surface waves ‘from and to’ the VNA.

Fig. 1(b) shows representative electrical field intensity 'E' of the output surface wave above the LSP sensor which gradually becomes weaker away from it. SHM application can be achieved successfully by understanding this principle of output surface wave intensities (amplitude) and their changes, obtained due to (a) vertical, (b) horizontal and (c) angular inclination of the LSP sensor. Contactless acquisition can be obtained i.e., signals can be captured in the air medium, by the receiver probe (either in X-Y plane or X-Z/ Y-Z plane (or Z axis) or parallel to these planes).

The input EM wave results in surface wave as output, that decays within the copper plate and the air medium above it, with two different non-linear curves along the negative and positive Z-axis as shown in Fig. 1(c). These curves represent surface plasmon/ wave in the copper metal and the air medium . This design was selected after weighing various pros and cons such as its resemblance, shape, size, properties, sensitivity and its performance compared to leading smart material sensors such as PE ceramic or macro fibre composite sensors. More about application of this design in SHM can be obtained from Annamdas and Soh [19, 28].

The surface wave decays above (+Z) and below (-Z) the interface of air medium and copper. Output response is acquired along Z-axis ($Z > 0$) in the air for a input (point source) below or above the LSP based on the concept of transportation of surface wave energy [52]. If there is any discrepancy in the monitored engineering ACM structure, then it gets identified by changes in the output surface wave intensities. Some of the other LSP designs have been explored in photonic energy transport [30], super-resolution imaging [53], cloaking [54] and waveguiding [55] but not for SHM.

The present design of LSP sensors can be implemented in confined and non-confined configurations. We already tested their applications in confined viz., contact and contactless configurations where the respective sensor was either in contact or contactless with the host beam [19, 28, 29]. The term 'confined' represents confinement of the surface wave zone above

the sensor or with-in its near vicinity. Figs. 2(a-b) shows a representative contactless configuration of the sensor where the EM waves were supplied in the radio (or microwave) frequency range to the LSP sensor that is extremely localized at the interface of (a) copper (X-Y plane) and (b) the dielectric medium (air) above the sensor in Z-direction [21, 39]. This results in a nonlinear 3D zone of evanescent surface wave that decays exponentially away from the interface as shown previously in Fig. 1(c).

Our previous studies illustrated that LSP sensor is effective in identifying the ‘deformations’ of a beam even if they are negligible in the order of $1/100^{\text{th}}$ of a mm. Furthermore, their sensitivity using a quantifiable statistical analysis viz. Root mean square deviation (RMSD) is at least 10 times larger than the contemporary PE sensors [28]. However, confined configuration has a limitation of acquiring output in a confined zone above the sensor and the measurement of subsequent scattered parameters is limited within the close proximity of the sensor. In this article, we present another important step in the development of these LSP sensors for SHM, by expanding the area of output diagnostic/ sensing zone above the sensor by transporting them via waveguides to far-off locations as similar to optical fiber cables transporting EM waves in FBG based sensing. Fig. 2(c) shows the proposed non-confined configuration comprising of an LSP sensor and a representative 1D metallic waveguide. The figure shows that there exists a surface wave area in the XZ plane as well as a surface wave zone in XYZ space; above the waveguide and the sensor respectively. The presence of large volumes/ areas of surface wave obtained in the present study facilitated the acquisition of unique health signals above the waveguide along the X-direction, in addition to the acquisition of health signals along Z- axis above the LSP sensor as demonstrated in our previous articles [19, 28, 29]. Thus, this paper explores LSP sensor and waveguide’s full potential for various laboratory specimens using confined and non-confined configurations to monitor deformations/ inclinations.

2. Waveguide and Robot Scanner

In EM optical fiber communication, the term waveguide refers to any linear structure that transports EM waves from one location to another, either with or without dissipation. There are different types of these waveguides with different cross sections available in the market. For example: transmission lines such as microstrip and coplanar waveguide, stripline, coaxial cable are some of the regular waveguides. In some applications, glass fibers are preferred to metal wires when waves need to travel with less dissipation loss in highly confined boundaries. Optical fiber cable used in FBG sensing is a special dielectric waveguide designed to transport, optical waves in a confined path. However, they are very fragile and can break in harsh environments. Hence, they are always packaged carefully to avoid breakages. The propagation of waves in metallic or any other dielectric waveguide is preferred when the travel path is not significantly large and dissipation loss is not a problem. The travel path depends on the type of confined waves which are influenced by total internal reflection. Some waveguides made of non-radiative dielectric materials, and the Goubau line (single wire transmission line) uses both metal casing and dielectric surfaces to confine the wave [56 – 60].

In the present article, we employed hollow and confined input and output co-axial cables of 6 m each, which respectively supplied input EM waves and acquired output surface wave from and to VNA. We also used a ‘conductive and solid’ lead cable of circular cross sectional diameter 1.5 mm as waveguides with their lengths ranging from 10 to 30 cm based on experimental types as presented in the later section (section 4). Selection and discussion of the waveguide are a technical topic in electronics or physics, but for ACM engineering,, the concept of using it effectively for SHM is more important. Thus, the present study is limited to demonstration of (1) the feasibility of waveguide’s application and (2) the combined potential of LSP sensor and waveguide.

These co-axial cables with dipole antennas were mounted on a 2D robot scanner as shown in Figs. 3(a-b). The components of this scanner were procured from YAMAHA [61] and assembled in Nanyang Technological University (NTU). The important component of the robot scanner (X-Y table) is a horizontal sliding arm, which can move in the X and Y directions rapidly (<1 sec for each move).

In our study, this robotic arm was used to hold and move one coaxial cable that supplied either input EM waves at intermittent predefined locations or acquired output surface waves at instructed locations, but not for both simultaneously (in future it can be programmable). The LSP sensor and the software to handle both the sensor and the robot are commercialized by an NTU startup company [62]. Thus the robotic arm facilitates scanning of structures rapidly and effectively with minimal human errors, as required for present and future SHM applications.

In this article, four experiments where two each using confined and non-confined configurations were carried-out:

First, metallic specimens viz., (1) shell and (2) beam made of aluminium (AL) with a Poisson ratio of 0.33, a density of 2715 kg.m^{-3} and Young's modulus of 66.67 GPa were adopted for confined configuration experiments (Figs. 4 and 6, see details in the sub-sections 4.1 and 4.2). For this purpose, LSP sensors of 'convex' and 'double bent' shapes were attached to shell and beam for monitoring angular and vertical deformations, respectively. These two experiments demonstrated the ultra sensitivity of this technique.

Next, non-metallic specimens viz., (1) concrete blocks of characteristic strength 30 N.mm^{-2} and (2) a standard bi-cycle tube of maximum pressure capacity 140PSI; with negligible EM conductions were adopted in non-confined configurations experiments (Figs. 8 and 10, see details in the sub-sections 4.3 and 4.4). For this purpose a flat and a curved shaped LSP sensor along with waveguides were attached on these specimens for monitoring of horizontal displacements and pressure.

3. Primary and Secondary Sensing

As stated earlier, confined configurations comprised of a single circular shaped LSP sensor, which is highly flexible, bendable and twistable which can assume linear (0°) to double bent (180°) shape based on the requirement of the monitoring structure. Thus, this LSP sensor can be termed as a primary sensor and it generated only one 3D surface wave zone as output (Fig 1b-c).

In non-confining configuration, in addition to the primary sensor, a metal waveguide is used for transporting EM waves/ surface waves. This waveguide is termed as the secondary sensor (Fig 2c).

In confined and non-confined configurations, the surface waves decayed within the sensor; and both within and along the length of the waveguide, respectively [63].

In confined configurations, the output surface wave intensity ' E_o ' changed non-linearly along the X or Y directions (X-Y plane) and along the Z direction (perpendicular to X- Y plane) of the primary sensor while in non-confined configurations, an additional surface wave area (extra zone) existed on the secondary sensor and whose intensity changed linearly along the X direction (in the X-Z plane). Thus, the output generated in this non-confined configuration comprised of 3D and 2D surface wave zones at the top of primary and secondary sensors which can be respectively termed as 3D output of the primary sensor and 2D output of secondary sensor.

Working principle: To understand the working principle of the LSP sensor in XYZ space, we start with the simplest form of surface plasmon propagating at the interface ($Z = 0$) of the copper and the dielectric (air medium) in which electric fields for transverse EM wave is written as [64, 28, 29]

$$E_o = \bar{E}_m e^{p_m Z} e^{i\kappa(x \cos \psi + y \sin \psi)}, Z < 0 \quad \text{and} \quad E_o = \bar{E}_d e^{-p_d Z} e^{i\kappa(x \cos \psi + y \sin \psi)}, Z > 0 \quad (1)$$

Where the subscripts m and d refer to the copper and air mediums, respectively. Similar expressions can be written for the magnetic field phasor H .

If P_m and P_d are positive real parts, then both electric fields will decay ($Z \rightarrow \pm\infty$) indicating localization within the vicinity of the interference at $Z = 0$ (i.e decays away from $Z = 0$).

Furthermore, the 1D waveguide placed along the X or Y direction from the center of sensor in non-confined configuration either transport input EM or output surface waves based on the experiment type as shown later. There exists a linear relation between the intensity of the waves and the length of travel based on the coefficients of attenuation and radiation absorption, scattering of photons, transmission loss, etc. The transports of input EM waves can be in any direction i.e along positive or negative X (or Y) direction which implied that the input waves can travel through it from one end or some intermittent location on it. These waveguides can also carry the output surface waves emanating from the top of the sensor. Thus, the waveguide that transfers input EM waves and output surface waves separately can be named respectively as an input waveguide (i.e. input coaxial cable) and an output waveguide (i.e output coaxial cable).

4. Experimental Studies

In the experiments, the input excitation EM wave in the radio frequency of bandwidth 3-7 GHz (200 sampling data points) was supplied to the cavities of the copper plate (spacing between elements) by the input dipole antenna (Fig 1a). The output dipole/probe measured the transmitted, scattered parameter - S_{21} at single or multiple locations along the Z-axis for a couple of experiments, and along the X axis (in the X-Z plane) for another couple of experiments using the sliding arm of the robot scanner (see Fig. 3a-b).

4.1 Inclination Assessment of Bent LSP Sensor

Fig. 4 shows the inclination assessment of a convex shaped LSP sensor, on the top of an aluminium shell in a confined configuration. Fig. 4(a) shows shell with convex curvature and two

LSP sensors, i.e. a top sensor and a side sensor, attached with cellotape on the external surface of the shell. This cellotape can be removed easily, so that sensor can be reused for other experiments. The LSP sensor can also be permanently bonded using any commercial glue or epoxy for permanent SHM applications, but in the present case, the sensor was later reused. The figure also shows the input-dipole, exciting the sensor from a distance of 3 mm with an inclination of 75° to output-dipole, probing at a distance of 7 mm. Fig. 4 (b) shows the curvature in the attached ‘top sensor’ attached to the shell, which is different on either side of its center. This resulted in a steeper slope on the right side while the side sensor is flat and was employed only for representation.

Fig. 4(c) shows illustration of a robotic arm, which hosts output/ probe antenna and input/ source antenna where the arm is automated to move along the probe line parallel to X axis. The figure also shows exaggerated views of the top and side sensors. In the normal view, the radius of the copper plate is 12 mm for flat sensor, but it got reduced to 10 mm for the top sensor due to the convex curvature of the shell. As stated earlier, the output cable was attached to the sliding arm of the robot (also see Fig. 3), which was instructed by a pre-defined software to capture signals along the probe line (in the X-Z plane) from the top of the point ‘a’ to point ‘A’. The figure shows that the point ‘M’ is located at the center of the copper plate, whereas the points ‘a’ and ‘A’ are located immediately outside the copper plate. Points from ‘b-B’ are located within the copper plate and the distance between subsequent points is 2 mm. During the experiment, the distance ‘d’ between acquisition line (probe line) and the point on the sensor increased until mid point and then decreased, gradually as the sliding arm moved from one point to another.

Fig. 5(a) shows three representative signals from among eleven transmitted signals during the movement of sliding arm from left to right. Technically, pairs of points ‘a – A, b – B, c – C, d – D, e – E,’ are similar and can be expected to have identical results, but the sensor is not exactly bonded on the top of the shell, and there was a slight inclination of about 3° and 1° on either side. Nonetheless, signals above points ‘a’ and ‘A’ generated similar magnitudes as represented at three

different peaks 1, 2 and 3. Figs 5(b-c) show close-up view of signals during decrease and increase of distance 'd' for a representative frequency range of 4.26 to 4.65 GHz. These signals are in accordance with the sensor's curvature on the top of aluminium shell.

To further understand the quantitative behavior of all the signals in different bandwidths, a widely accepted sensing index, i.e root mean square deviation (RMSD) index was adopted as given below

$$\text{RMSD (\%)} = \sqrt{\frac{\sum_{i=1}^N (y_i - x_i)^2}{\sum_{i=1}^N x_i^2}} \times 100 \quad (2)$$

Where $i = 1, 2, 3 \dots N$ represents sampling data points in the considered frequency range. x_i is the baseline signal obtained above 0 mm (at a) for all the N considered sampling points. While y_i represent subsequent signal at the later condition for all the N considered sampling points. $j = 1, 2, 3 \dots$ represent the number of such subsequent signals at the later conditions (such as 2 mm to 20 mm). This is schematically illustrated with a baseline signal and 2 subsequent signals in a representative Fig 5(d). RMSD indices are computed based on the quantitative difference between normal curve with dotted curves at points $N = 1, 2, 3 \dots 200$. The signal can be normal or the logarithmic value obtained from the data logger / analyzer, but RMSD is always stated as a % variation of a signal (y_i) with the baseline signal (x_i). Thus, there can be many RMD values based on the number of signals (i.e j) obtained for various condition. This RMSD index has been widely used over the decades by ACM engineering groups [19, 65,66,67].

Table I shows the RMSD indices obtained at various horizontal distances from 2 mm to 20 mm for three different bandwidths viz., 3 - 7 GHz, 3 - 6 GHz and 4.15 - 4.6 GHz. RMSD indices increased until midpoint and then decreased continuously for all the bandwidths. The slight inclination of the LSP sensor on the top due to convex curvature of the shell, which was not clearly observed in the signals got indicted in the statistical index, i.e. RMSD indices show a clear difference in magnitudes for points b-B (2-18 mm), c – C (4-16 mm), d-D (6-14 mm) and e-E (8-

12 mm). Curvature of the LSP sensor is different on either side of at the mid point M(10 mm) , which is visible from the greater magnitudes of RMSD on the right side at BC, D and E (i.e 16 mm to 12 mm) compared to lower magnitudes on left side (below 10 mm).

In this experiment, the acquisition of output as stated earlier was considered along the X direction (in the XZ plane) above the primary sensor, unlike our previous work [28], where the measurement scope was considered only in the Z-direction (perpendicular to the plane of the sensor). Thus, in this experiment, we validated the LSP sensor for its sensitivity along the X or Y axis (parallel to the plane of the sensor) in addition to our previous validations along the Z axis.

4.2 Load Monitoring using Double-bent LSP Sensor

Fig. 6 shows a fixed-fixed beam subjected to transverse loading at the center where a double bent LSP sensor is attached with a cellotape and a hanger of 1N weight was hung. The input and output dipole pointed towards the same sensor, one below and other above the beam. Two loading tests were carried out by changing output dipole distances. In the first loading test, a total cumulative load of 11N was hung at the center in 10 incremental steps in the order of four 0.5N, four 1N and two 2N weights. The input dipole was at a distance of 5 mm below the beam throughout the loading test from 1N to 11N, whereas the output dipole was 3 mm above the beam and it increased as the beam deformed by ' Δ ', as depicted in Fig 7(a). The increase in loading reduced the magnitude of signals because the output distance increased continuously. This indicated that the shifting in magnitudes of signals increased, which also increased the statistical RMSD index; from first loading step to the tenth step as listed in Table II.

In the second loading test, the initial distance between input dipole and the beam was continued to be 5 mm, but the output antenna distance was increased to 8 mm. Loading test was again carried out from the first step to the sixth step uninterruptedly. Later, a weight of 1N accidentally fell on the beam which disturbed the experimental setup including a change in output probe distance. The output dipole moved closer to the beam by 3 mm to a new value of 5 mm

resulting in a substantial gain in the signals as shown in Fig 7(b). The test was continued from the next step until the tenth step. These eleven signals can be divided into two sets where the first is prior to the accident and the second after the accident. Both the first and second sets show gradual downward shifting similar to the first loading test, but the second set shifted from a higher magnitude that resulted due to impact. The accident increased the RMSD massively from 10.1% to 41.7% at the loading of 5N. However, there existed increase in RMSD for all the ten steps throughout the test.

The deformations in these two tests are the same and were calculated using the classical beam theory for loading at the center of a beam as given below [68]

$$\frac{WL^3}{192E_sI_s} \quad (3)$$

Where W is the load magnitude on the center, L (=32 cm) is the effective span measured between the centers of each support/ end, E_s is elastic modulus, I_s is the area moment of inertia. The term E_sI_s (=1227310 N/mm²) is the flexural rigidity which depends on the dimensions and properties of the beam material. Table II also lists the deformation of the beam under the applied load. Furthermore a slight increase in deformation of 0.21 mm to 1.53 mm for a load increase of 1.5 N to 11 N, (a difference of a mere 1.32 mm in a load increase of 9.5 N) increased the RMSD by almost 5 times, which demonstrates the ultra sensitivity..

These loading tests using the double bent configuration of LSP sensor, along with two earlier loading experiments conducted by our group in contact and contactless configurations in absence of any bending of sensor [28, 29] demonstrated that these sensors are very sensitive either in normal or in bent configurations.

4.3 Displacement Monitoring using LSP Sensor and Input Waveguide

Fig. 8 shows two displacement tests for concrete blocks using non-confined sensor configuration where a lead metallic waveguide of 18 cm was used in addition to LSP sensor. The waveguide was spread (laid) from the center of the sensor to one end of a concrete block as shown in Fig. 8(a). Concrete is less conductive with lower dielectric coefficient compared to the lead metal and it does not interfere much with the flow of EM waves in the waveguide [69]. The input dipole was connected to the sliding arm of the robot at distance 5 mm above the waveguide level, and the output was attached at a fixed position of 4 mm above the LSP sensor as shown in the figure. Thus the primary sensor and the output dipole above it were placed on a fixed platform, whereas the input dipole pointing towards the input waveguide, attached to the robotic arm moved from left to right in pre-considered intervals/ selected distances. Thus the input was provided to the primary sensor via the input waveguide along the X-direction (in the X-Z plane) at selected locations as shown in Figs. 8(a-d).

In the first displacement test, input was supplied eight times at eight representative locations viz., 0 cm, 0.5 cm, 2 cm, 2.5 cm, 3.5 cm, 4 cm, 5.5 cm and 6 cm from the edge of the primary sensor with the movement of sliding arm from left to right as shown in Fig. 8(a). Subsequently, eight signals were acquired from a fixed output location above the primary sensor, and their magnitude continuously reduced as the input distance increased as shown in Fig. 9(a). This test demonstrated that if the travel path of the input EM waves increased, then the magnitude of the signal decreased and vice versa. This test was a preliminary assessment to understand the efficiency of input waveguide for a representative displacement monitoring.

Generally in civil structures such as buildings or bridges, any change in the distance between two adjacent concrete structural components (beam and column) can create a crack and thus monitoring of gap/ displacement between structural components is very important. Very recently, such displacement monitoring was carried out by Ashraful and Sergey [70] for smaller

separations less than 1 cm (adopting a different metamaterial design). However, our experiment adopted a much simpler design can monitor displacements that are either small or very large. A second displacement test was carried out based on the results of the first displacement test, aimed to monitor displacement between two adjacent concrete blocks as shown in Figs 8(b-d). In this displacement test, two concrete blocks viz., a fixed block 1 and a movable block 2 were separated by a random distance. The input dipole was attached to the robotic arm, which was held at 5 mm above the top of the block 2. The output was captured at the top of primary sensor located on fixed block 1 as similar to the first test. The robot arm tracked the travel path of block 2 by moving the input dipole wherever it moved along the X- axis. The output was obtained when block 2 was separated by certain representative distance viz., 1 cm, 2 cm, 2.5 cm, 3.5 cm, 4 cm, 4.5 cm, 5.5 cm, 6.5 cm and 7.5 cm away from block 1. Fig. 9(b) shows the output signals during separation of two concrete blocks, which are similar to Fig. 9(a). These two displacement tests show the successful application of input waveguides, which transferred/ guided input EM waves from VNA towards the LSP sensor from different locations. The next experiment shows application of an output waveguide, that was used to transfer the output surface wave from within the sensor to far off locations.

4.4 Bicycle Tube Monitoring using LSP Sensor and Output Waveguide

Figs. 10 and 11 show monitoring of bi-cycle tube during the pressure increase from 20 psi to 120 psi in steps of 20 psi. The tube was hung on a small table stand, and only a part of the tube was supported as shown in the figures. An LSP sensor was attached to the tube using a cellotape and a portion of the output waveguide was wrapped around the tube from the sensor as shown in Fig. 10 (a). The length of wrapped and unwrapped output waveguide was respectively 20 cm and 30 cms. The input and output probes were pointed towards the sensor and waveguide at the respective distances of 7 mm and 3 mm, which remained the same throughout the experiment as shown in Figs 10(a-c). Figs 10(c-d) show the overall diameter of the circular tube and the length

of the unwrapped part of the waveguide. There exist changes in the configuration and increase in ‘supported length’ of the tube during pressure increase. Furthermore, the vertical distance of the tube above the table stand increased in steps viz., 1 cm (= h_1), 1.4 cm (h_2), 1.7 cm (h_3), 4 cm (h_4), 5 cm (h_5) and 6 cm (h_6) during corresponding pressure increase viz., 20 psi, 40 psi, 60 psi, 80 psi, 100 psi, 120 psi, respectively. This experiment presented the measurement of output surface wave intensity on top of the output waveguide i.e. secondary sensor as shown in Fig. 11. Furthermore, the curvature changes and the pressure increase were also assessed using RMSD indices as given in Table III. There was no linear increase either in the signal magnitudes or in the vertical distance or RMSD indices, because the pressure caused no significant increase in the tube diameter initially, but drastically changed after the fourth increment till the end. This is because there existed a pre-manufactured diameter of the tube which increased only after a certain pressure. Nonetheless, these increments were captured by the surface wave output, that traveled all the way from the sensor through wrapped and unwrapped lengths of the output waveguide. In the previous experiments, output was measured above the primary sensor, whereas in this it was measured above the secondary sensor.

All these experiments successfully presented both the application of primary and secondary sensors for the first time in SHM.

5. Conclusions

This paper presented the engineering application of near-field based EM metamaterials such as bendable LSP sensor and waveguide that obtained unique surface wave zones for SHM applications. The potential for widespread acceptability of these types of metamaterials in near field was discussed as they do not need isolated anechoic chambers. Further, the future of metamaterial applications is bright for SHM as these LSP sensors have recently been commercialized.

All the experiments reported here as well as data obtained in our facility over the last few years show that LSP can work in contact or contactless configurations. That is, confined configurations when used alone as well as in non-confined configurations when used in the presence of the waveguides. The role of the waveguide is that of the secondary sensor which transports (a) input EM waves to activate the primary LSP sensor as presented in displacement monitoring of concrete block and (b) output surface waves from within the primary LSP sensor to far-off distance as seen in bi-cycle tube monitoring.

In this study, we have not only carried forward our previous work which was limited to the application of primary LSP sensor in either contact or contactless configurations, but its applicability using a novel combination of a robotic arm and a waveguide was demonstrated. In this paper, four experiments were carried out viz. (1) Convex shaped LSP sensor for inclination monitoring: signals measured along X direction above the primary sensor along with a statistical RMSD index were effective to show variations even for the slight inclination of the sensor. (2) Double bent LSP sensor for load monitoring: signals measured along Z- axis were effective in showing variations even for fractional changes in deformation of the beam. (3) Normal LSP sensor with input waveguide for displacement monitoring: waveguide was used as input aid that transferred input EM waves to monitor displacement between blocks. (4) Normal LSP sensor with output waveguide which was partly wrapped and partly unwrapped for monitoring bicycle tube configuration: waveguide was used as output aid that transferred surface waves. The signals were capable of showing changes in ‘amplitude’ alone while the statistical ‘RMSD index’ measured the sensitivity of these signals. Thus, both amplitude and RMSD measurements were used to demonstrate the application of LSP sensor for monitoring deformation in the order of ‘mm’ in load test to ‘cm’ in separation of the concrete block test. During load monitoring test, a small accidental fall of a weight was also captured in the signals and also in the subsequent RMSD indices which showed the effectiveness of these sensors for

loading as well as impacts. The combined application of primary and secondary sensors increases the measurement scope of metamaterials for present and future SHM. All these experiments were executed using a robotic arm scanner that provided faster acquisitions on top of both the primary LSP sensor and the secondary waveguides. Importantly, these sensors are at least 10 times more sensitive than the existing smart material such as piezo electrics as presented in our previous articles. In future, these laboratory studies can be extended to real applications by permanently bonding LSP sensors to specimens for long term monitoring with automated 3D robots so as to reduce human errors.

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Figure 1. Design of metamaterial LSP sensor (a) LSP sensor and vector network analyser (b) sensing zone in near field (c) representative surface waves in +ZX and -ZX planes for air medium and copper

Figure 2. Implementation of LSP sensor – waveguide (a) LSP under the beam in front view (b) LSP under the beam in isometric view (c) representative 3D and 2D surface wave intensities above LSP sensor and waveguide

Figure 3. Robotic arm scanner (a) isotropic view and (b) top view

Figure 4. Aluminium shell specimen (a) photo (b) sketch and exaggerated view with details (c) details of acquisitions in X-Z plane above the top sensor (bent) and details of side sensor (flat).

Figure 5. Signals obtained during inclination monitoring (a) three representative peaks and their comparisons (b) continuously increasing peak during robot movement from points 'a' to 'M' (c) continuously decreasing peak during movement from points 'M' to 'A' (d) illustration of RMSD index using sample signals.

Figure 6. Aluminium beam specimen subjected to loading tests

Figure 7. Signals during loading tests (a) first test (b) second test

Figure 8. Displacement monitoring tests (a) photo and details of preliminary assessment for displacement monitoring (b) displacement between two adjacent concrete blocks : 1 cm (c) 4 cm (d) 7.5 cm

Figure 9. Signals of displacement tests (a) preliminary assessment (b) distance between concrete blocks

Figure 10. Tube specimens with details of wrapping of waveguide and attachment of LSP (a) photo of tube monitoring setup (b) LSP and wrapped part of waveguide (c) view of bi-cycle tube (d) input-output details.

Figure 11. Signals obtained during increase in tube pressure

Table I. Shell specimen

Distance (mm) (X- direction)	RMSD(%)		
	[3 – 7 GHz]	[3 – 6 GHz]	[4.15 – 4.6 GHz]
2	5.27	5.45	2.51
4	27.1	28.6	20.1
6	50.6	53.4	87.5
8	57.0	60.2	111
10	78.6	83.1	159
12	67.6	71.5	146
14	61.8	65.3	117
16	56.5	59.6	71.2
18	52.6	55.4	45.5

Table II. Load specimen

Load (N)	RMSD(%)		Displacement (mm)
	[first test]	[second test]	
1	-	-	-
1.5	9.76	4.54	0.21
2	21.1	6.44	0.28
2.5	24.6	8.79	0.35
3	29.2	9.81	0.42
4	33.1	10.1	0.56
5	34.0	41.7	0.70
6	45.2	118	0.83
7	49	103	0.97
9	52	105	1.25
11	53.6	92.6	1.53

Table III. Tube specimen

Configuration	Tube pressure (psi)	RMSD(%)
1	20	-
2	40	22.5
3	60	42.7
4	80	44.1
5	100	612
6	120	727