Design of Frequency Selective Devices for the THz Domain with Applications on Structural Health Monitoring

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Abstract – **In this paper, a study on the transmittance as a function of applied force for a new THz sensor is proposed. The sensor consists of two frequency selective surfaces (FSSs) based on metamaterial wire resonators and works as a re-configurable selective THz filter in which only radiation of certain desired frequencies is allowed to pass. Numerical modelling of both the mechanical and electromagnetics behavior of the sensor is reported for a device assembled with a High-Density PolyEthylene (HDPE) thermoplastic polymer host at a target frequency of 408 GHz.**

I. Introduction

In engineering, structures are routinely inspected to identify failures and their effects on structural stability. Structural Health Monitoring (SHM) is the multidisciplinary field that has pioneered the study of novel technological solutions that identify structural damage and allow a more efficient monitoring of engineering structures, such as the state of conservation of buildings [1]. Terahertz (THz) is a rapidly emerging field in science where there is an urgent need for new ways of producing sources, detectors and other devices such as filters, sensors and modulators. Artificial materials, such as metamaterials, play an important role in THz because it is possible to fabricate very compact and extremely selective structures, known as frequency selective surfaces (FSS), surpassing the performance of existing materials in nature [2]. Recent studies on the application of THz technologies in SHM refer to the measurement of displacement in engineering structures and to imaging systems that detect cracks and other structural issues [3,4]. In this paper, we present an electro-mechanical sensor for SHM that operates in the THz range made of two FSS (arrays of wires) within a dielectric host, as shown in Fig. 1a). More specifically, we study the transmittance of the sensor as a function of the applied compression along the x-axis. When the sensor is compressed the distance between wires d decreases and therefore the frequency response of the sensor is also changed, as shown in Fig. 1b). The bell-shaped frequency response is obtained from the selective character of the wire arrays. The sensor is used at the target frequency where by applying more or less compression it is possible to set the sensor response to complete opacity, complete transparency and all degrees of transparency in-between. The proposed sensor has a simpler design than that presented in [2] allowing for lateral compression rather than uniaxial compression which is an improvement on its functionality and applicability. It is more selective because its operating principle is based on resonance of two wire arrays in the propagation directions and a careful design of the d/a ratio of the wire arrays (a is the radius of the wires), enhancing the q-factor of the sensor's filter.

II. Filter theory and design decisions

In Fig. 2, we show a diagram of one of the arrays of wires that compose the structure and the associated electromagnetic modes in a $k_x - k_z$ diagram which is a direct consequence of the periodicity of the structure in the x direction. When a wave is incident on the wires, reflected and transmitted waves are generated but the amount of energy transferred to the resulting waves is controlled by these modes. The distance between wires dictates the position of the modes in the diagram and it can be chosen so that all modes are evanescent. This requires that the distance between wires must be smaller than the wavelength of the incident wave λ, a condition that can be easily derived from the diagram in Fig. 2b). However, we assume a stronger criterion and shall impose that d is smaller

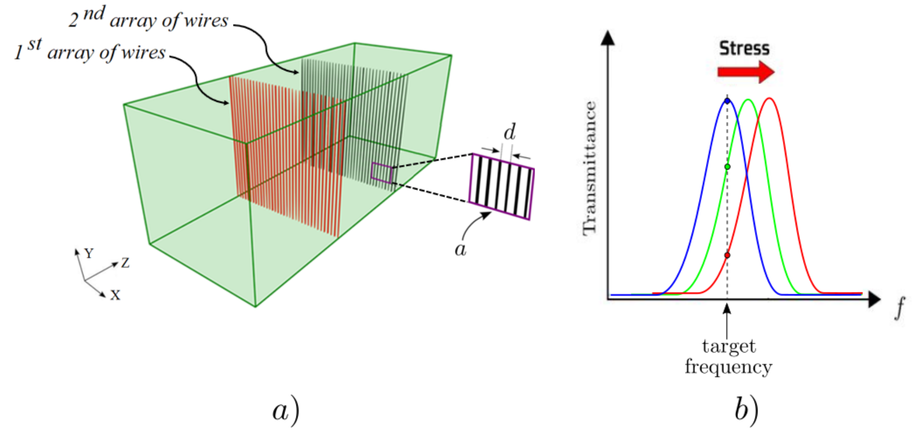

Fig. 1: Overview of the working principle of the proposed stress sensor.

that $\lambda/2$. The energy of these waves is then concentrated in the vicinity of the wires and due to this energy storage the array of wires can be described as an admittance Y in an equivalent circuit of the sensor, where Y is given by

$$Y = j\frac{\lambda}{d}\frac{2\,Z^{-1}}{\ln\left[2\left(1-\cos\left(\frac{2\pi a}{d}\right)\right)\right]}, \tag{1}$$

a is the radius of the wires and Z is the characteristic impedance of the host material. Using two equally spaced

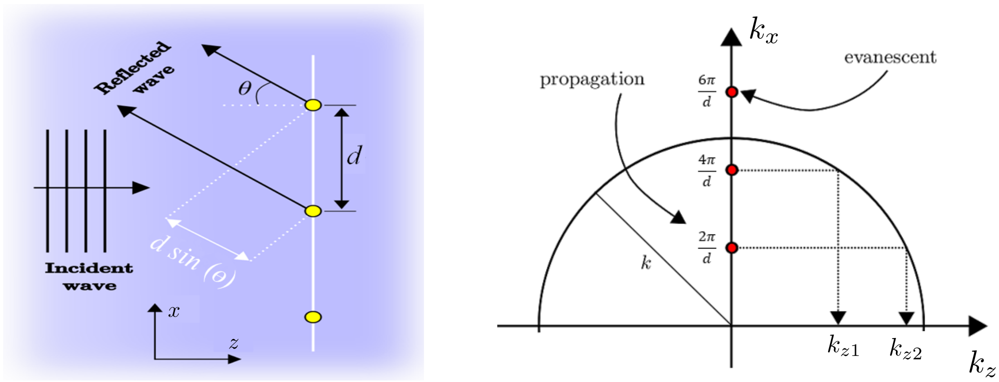

Fig. 2: Wire structure geometry and its $k_x - k_y$ diagram.

wire grids, as shown in Fig. 1a), the structure will present a highly selective bell-shape frequency response whose quality factor and resonant frequency is controlled by the values of d and Y. Increasing the value of Y the sensor will be more selective in frequency and so more sensitive to pressure changes. In the sensor design we first decide on a value for d and then we can control Y by adjusting the radius of wires a. The theory, however, is only valid for thin wires so we must ensure that $a \ll d$. Regarding the choice of the host material, Naftaly refers that silicon and plastics such as HDPE and PolyTetraFluoroEthylene (PTFE) are key terahertz materials since they present low losses and low dispersion in the THz frequency band from 0.1 to 5 THz [3]. In this study, HDPE was considered because it owns a linear structure with few branches that gives it a very good strength/density ratio, making it relatively easy to compress [5]. We assume that it is possible to compress HDPE up to 25 % of its original size without harming its functionality. The sensor is designed to operate at frequencies between 395 and 455 GHz. A battery of tests consisting of electromagnetic and mechanical simulations were performed to find a good set of parameters for the correct functioning of the sensor in the desired range: a distance between wires $d \in [0.015; 0.02]$ mm, wire radius $a = 0.0002$ mm and total length of host material $l = 1.42$ mm. The distance between wires was defined as a range in order to account for the possibility of having several levels of compression.

III. Electromagnetic and mechanical simulation results

The results of our numerical simulations using the parameters and host material outlined in the previous section are shown in Fig. 3 for a target frequency of 408 GHz. In Fig. 3a) we can see that the sensor has a good dynamic range because its transmittance can take values between 1 (no compression) and 0.15 (at 25 % of compression). The transmittance as a function of the applied force is shown in figure 3b) for mechanical structures consisting of 10, 30, 50 and 70 wires. In these tests we compressed the sensor beyond the 25% limit defined above (for mechanical testing purposes that we will not discuss here) but we can see that it would be possible to obtain total opacity (zero transmittance) by further compressing the material. As a final comment, note that the sensor response is quite linear in the range of interest (transmittance above 0.15), especially in the cases we consider more wires.

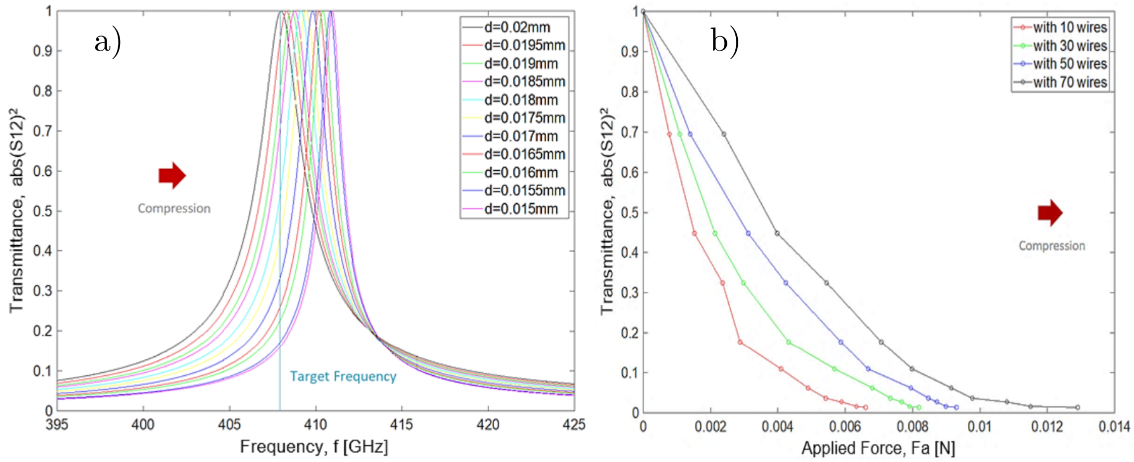

Fig. 3: transmittance in the frequency domain a) as a function of distance between wires and b) as a function of applied force for 10, 30, 50 and 70 wires.

IV. Conclusion

In this paper, a new stress sensor for the THz range was proposed using an architecture based on two FSSs. Electromagnetic and mechanical simulations have been performed to corroborate the working principle of the sensor and find a good selection of parameters so that it works at the target frequency of 408 GHz with a good dynamic range and approximate linear response. In the mechanical simulations we have considered four different cases with 10, 30, 50 and 70 wires and concluded that the higher the number of wires the more linear the sensor response in the desired frequency range. For 70 wires the sensor has a sensitivity of around 106.3 N^{-1}.

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