ANALYSIS OF CIRCULAR MICROSTRIP PATCH ANTENNA TO DETECT STRAIN USING METAMATERIAL

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ABSTRACT

In this paper the feasibility of using a circular microstrip patch antenna to detect strain has been investigated. The theoretical model shows a linear relationship between strain as a function of temperature and the shift in the resonant frequency of the antenna. It has been shown that strain could be detected using a circular patch antenna and therefore could be detected wirelessly. The need for a structural health monitoring (SHM) system which could be more reliable and accurate to locate the damage in structure and specify its size and location still exists. The ultimate intention of this work is to configure antennas or resonators for the detection of relatively small damage zones in structures and to do so wirelessly.

NOMENCLATURE

a	radius of microstrip patch antenna
a_e	effective radius of microstrip patch antenna
a_{es}	effective radius of microstrip patch antenna after applying strain
c	speed of light in free space
c_1	constant number one
c_2	constant number two
f_r	resonant frequency of antenna
f_{rs}	resonant frequency of antenna after applying strain
h	thickness of antenna substrate
t	thickness of microstrip patch antenna
ε	strain
ε_0	permittivity in free space
ε_r	relative permittivity of antenna substrate
μ_0	permeability of free space
∇f	shift in resonant frequency

INTRODUCTION

Recent work has shown the effect of different parameters on the resonant frequency of microstrip patch antennas [1], [2]–[7]. A meta-material based wireless strain sensor consisting of an array of split ring resonators has been proposed recently [8]. This sensor is suitable for medical applications where the short distance between sensor and receiver is not a problem. However, for industrial applications such as SHM the effect of distance from reader, and the ability to locate larger strains makes it impractical. Tata in [9] shows that rectangular microstrip patch antennas could be used not only for communication between sensor and receiver, but also, as a strain sensor itself. However, it assumes that the Poisson's ratio of the antennas 'substrate and patch metal are the same. The designed antenna needs to work in two different frequencies and only detects strain in two directions while a circularly polarized circular patch antenna could be able to detect strain regardless of its direction.

In this work the relationship between strain as a function of temperature and the resonant frequency of a circular microstrip patch antenna has been investigated. A linear relationship has been derived from theoretical formulas. It has been shown that strain could be detected using a circular patch antenna and therefore could be detected wirelessly. The need for a structural health monitoring (SHM) system which could be more reliable and accurate to locate the damage in structure and specify its size and location still exists.

Wireless sensors can eliminate the wiring problem of the traditional SHM systems and reduce the maintenance costs associated with it [10]–[12]. Wiring is especially difficult for rotating composite components such as helicopter blades, rotor shafts, and wind turbine blades. A wireless sensor reduces the weight of the structure and its complexity. Most of the work in the literature investigates the feasibility of applying a wireless communication device to existing sensors to transfer information or power to and from sensors in different disciplines such as civil industry [13]–[16], and medical applications [17]–[20].

ANALYTICAL MODEL

In recent years microstrip antennas have been widely used in microwave frequencies and have been integrated in many electronic devices [21]. This popularity is because of their compact and adaptable size, inexpensive printed circuit board technology, and ease of integration with related electronics. A typical circular microstrip patch antenna is shown in Fig 1. The antenna consists of a very thin layer of copper as a patch, a layer of substrate, and the ground plane (A thin layer of copper). Substrate thickness is usually between 0.003 and 0.05 of free-space wavelength and their dielectric constant is usually between 2.2 and 12. For the application of sensor, the substrate thickness should be small and the dielectric constant should be large enough so that the antenna becomes narrowband. As a result, any shift in the resonant frequency of the antenna will become more clear, and easy to measure.

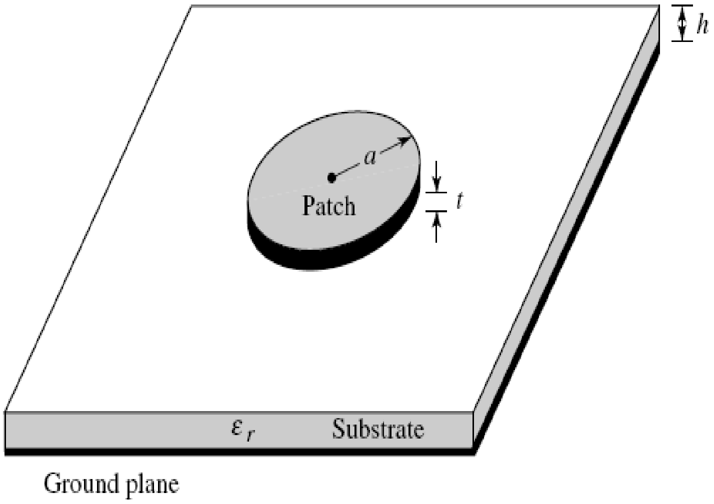

Fig 1 A typical circular microstrip patch antenna

According to the resonant frequency of a circular patch antenna with the radius of a , and substrate thickness of h and relative permittivity of ε_r is given by

$$f_r = \frac{1.2412\,C}{2\pi a_e \sqrt{\varepsilon_r}} \qquad (1)$$

Where

$$C = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \qquad (2)$$

the effective radius of antenna is

$$a_e = a\left\{1 + \frac{2h}{\pi a \varepsilon_r}\left[ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2} \qquad (3)$$

Let $$C_1 = \left\{1 + \frac{2h}{\pi a \varepsilon_r}\left[ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2} \qquad (4)$$

Thus, from (3) and (4)

$$a_e = C_1 \,.\, a \qquad (5)$$

and from (1)

$$f_r = \frac{c_2}{a_e} \qquad (6)$$

Where

$$c_2 = \frac{1.2412\,C}{2\pi\sqrt{\varepsilon_r}} \qquad (7)$$

After applying strain, effective radius of antenna is:

$$a_{es} = a_e\,(1 + \varepsilon_s) \qquad (8)$$

The dielectric constant as a function of temperature can be expressed as

$$\varepsilon_s = \varepsilon_0\,(1 + \beta\, T) \qquad (9)$$

substituting (9) in (8) we get,

$$a_{es} = a_e\,(1 + \varepsilon_0\,(1 + \beta\,T)) \tag{10}$$

Thus, from (6) and (10) resonant frequency of antenna is:

$$f_{rs} = \frac{c_2}{a_{es}} = \frac{c_2}{a_e\;(1+\varepsilon_0\;(1+\beta\,T))} \tag{11}$$

Hence, the frequency shift is:

$$\nabla f = f_{rs} - f_r = \frac{c_2}{a_e}\;\left(\frac{1}{(1+\varepsilon_0\;(1+\beta\,T))} - 1\right) \tag{12}$$

Thus,

$$\frac{\nabla f}{f_{rs}} = \frac{\frac{1}{(1+\varepsilon_S)}-1}{\frac{1}{(1+\varepsilon_S)}} = -\varepsilon_S \tag{13}$$

The antenna used for analytical calculations has the resonant frequency of 1.5 GHz, patch radius of 27.1 mm, substrate thickness of 1.5 mm, and the substrate is FR4 Epoxy with the permittivity of 4.5 and Poisson ratio of 0.12. The value of ε_o = 38.33 and $\beta = 3.82\text{x}10^{-4}\,/^{o}\text{c}$ for lithium niobate. These results are based on pure tension and with the assumption that the radius of the patch antenna changes in all directions with the same rate. The result obtained as the percentage of frequency shift has a linear relationship with strain as shown in Fig .2.

Among the numerous substrates available for the design of microstrip patch antennas with the dielectric constant of ($2.2 \leq \varepsilon_r \leq 12$) the most suitable ones for good antenna performance are thick substrates with a lowest dielectric constant . This is because they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space (at the expense of larger size) (Balanis, 2005). Thin substrates with higher dielectric constants (desirable for microwave circuitry) have greater losses and are less efficient and have relatively smaller bandwidths (Balanis, 2005).

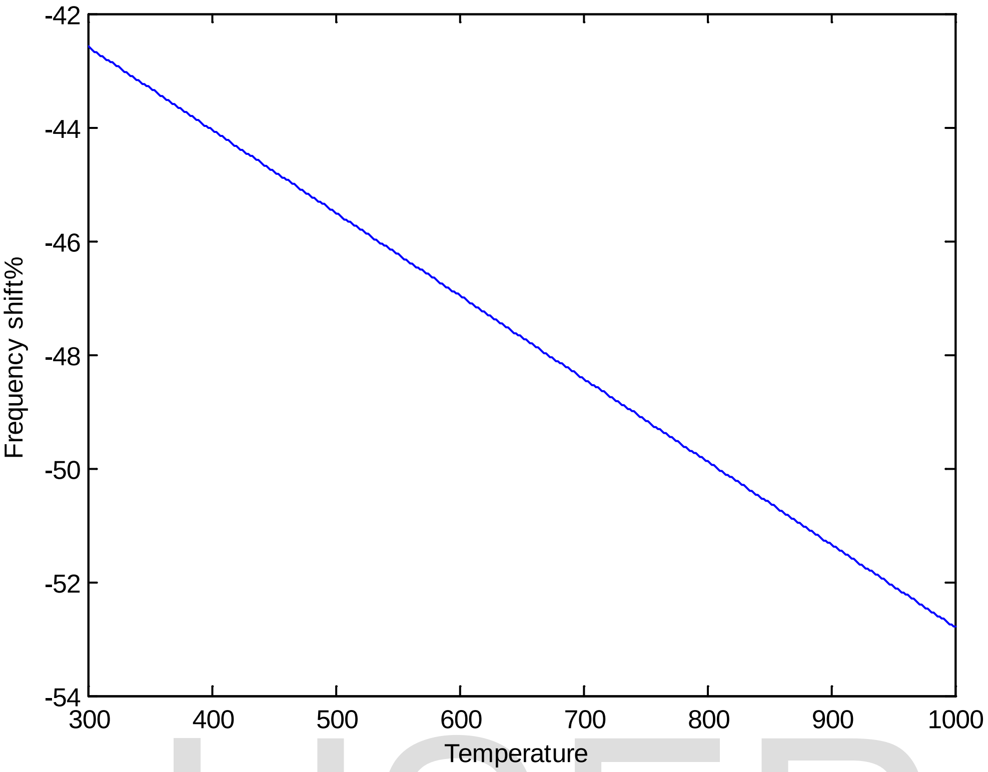

Fig 2 Linear relationship of strain as a function of temperature and frequency shift

RESULT

Finally, the feasibility of detecting strain using a circular microstrip patch antenna has been shown using theoretical studies, we can see the percentage of frequency shift has a linear relationship with strain as a function of temperature as shown in Fig .2. A miniature microstrip patch antenna could detect strain and possibly damage in the structure with more accuracy because a small strain will make a bigger shift in the resonant frequency of the antenna. It seems that an array of antennas or meta-materials has the potential to detect damage wirelessly for in-situ health monitoring. As a result weight, cost and complexity of the SHM system could be decreased. Therefore, more sensors could be embedded in a structure which results in a better performance and increases the reliability of the monitoring system.

CONCLUSION

The relationship between the shift of the resonant frequency of a circular microstrip patch antenna and the strain as a function of temperature applied to the antenna discussed in theory has been compared. The formulation derived shows a linear relationship between strain as a function of temperature and frequency shift.

We can see the percentage of frequency shift has a linear relationship with strain as a function of temperature as shown in Fig.2.With theoretical results which confirmed the feasibility of using a circular patch antenna to detect strain. This antenna sensor could be further developed for wireless SHM applications. A wireless sensor could eliminate the use of wires in SHM applications and therefore decrease the Complexity and weight of the sensory unit. This also increases the reliability of the SHM system because wires inherently increase the potential disconnection points in a wired sensory network. The antenna sensor also has an advantage over available wireless sensors by obviating the need for a battery.

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