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# Design of highly sensitive temperature sensor based on photonic band gap structure

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In this paper, a novel microstrip resonator technique for temperature sensing is proposed, designed, and implemented using a hybrid planar microstrip line and photonic band gap (PBG) structure. To implement the PBG structure of the microstrip line, a microfluidic channel with periodic form is introduced into the substrate and filled with water. The operation principle of the sensor is based on a frequency shift due to the variation in the center of the band gap, which in turn changes with the variation of the permittivity of water, which relates to the temperature. The different empirical expressions describing the complex permittivity with the resonant frequency were carried out. The proposed sensor is simple in design and low cost, which may be applied in different applications at the industrial.

Keywords: temperature sensing, photonic band gap structure (PBGS), sensor, microstrip.

## 1. Introduction

In biological and chemical applications, the temperature is an important parameter to be measured because most liquid's characteristics are sensitive to the variation in this parameter. The temperature measurement techniques can be classified based on the nature of contact between the measuring device and the medium of interest, and they are usually divided into three categories: invasive, noninvasive, or semi-invasive [1]. In the invasive technique, the temperature sensor is in direct contact (using a cable to the measurement instrument) with the medium of interest, as an example is mentioned in [2]. Unlike the invasive technique, in the noninvasive temperature measurement techniques, the variation of the temperature is observed remotely without the need for direct contact with a medium of interest. However, it is very expensive and requires high precision instruments compared to the invasive technique. Infrared thermography [1] is an example of the noninvasive technique. For semi-invasive temperature sensing, the sensor is in contact with the medium of interest, and the temperature is observed remotely, as proposed in [3].

Over the past decades, many wireless sensor technologies have been extensively studied for semi-invasive temperature sensing in different configurations, such as battery-powered wireless sensors [4], which is proposed for indoor and outdoor temperature monitoring. Passive wireless sensors [5] where the temperature is measured are based on the perturbation in the resonant characteristics of the LC circuit. To increase the interrogation distance, a new class of wireless temperature sensors was proposed in [6,7], based on the antenna backscattering.

The microstrip line is becoming increasingly popular, due to its ease of fabrications, relatively high-$Q$ factor and ease integration with other planar technologies. Various research studies on microstrip patch antenna temperature sensing in different configurations have been conducted [8-10].

The photonic band gap (PBG) structure corresponds to a design where the wave propagation is forbidden in certain directions within a certain band of frequencies of the structure [11]. For microstrip technology, the first approach of realizing a PBG structure was proposed in [12]; it consisted of drilling periodic holes in the substrate of the microstrip line. To simplify the structure, another design was proposed in [13] by etched a periodic pattern consisting of circles in the ground plane. The depth and bandwidth of the stop band in PBG structures depend on several properties, such as the permittivity of the substrate, the filling ratio between the substrate and the material in the holes [14]. The use of microstrip line based on PBG structure for liquid dielectric sensing applications is proposed in [15].

In this paper, we present for the first time the use of the properties of the stop band from the PBG structure of microstrip line resonators as a means of temperature sensing applications. The proposed structure shows temperature sensitivity depending on the variation of the center of band gap in the PBG microstrip resonator.

## 2. Design consideration and sensing principle

To synthesize the PBG microstrip structure, a triple-layer substrate (Sub1, Sub2 and Sub3, see Fig. 1) are used with a cyclic microfluidic channel that was introduced into the middle substrate (Sub2). The width of the unit cell ($d_2$) of the cyclic microfluidic channel is short because the fields in the microstrip line are concentrated near the line. The top is a 50 Ω microstrip on a very thin substrate (Sub1) and the bottom surface is a conductor plane on a very thin substrate (Sub3) as well. In Fig. 1, $a$ is the radius of the microfluidic channel and $p$ is the unit cell size. As the fields are concentrated in the microstrip structure near the line from it, to create the PBG microstrip resonator we pull the microfluidic channel away from the microstrip line in the middle of the uniform PBG structure on one side by a distance of $s$ to avoid the fields close to the line, which leads to the creation of two PBG reflectors. A 50 Ω microstrip transmission line with length $l$ that acts as a resonant cavity separates the two PBG reflectors (Fig. 2).

The optimal frequency for resonant design is the frequency corresponding to the maximum reflection coefficient in the two reflectors [16]:

$$f_{\max} = \frac{c}{2\sqrt{\varepsilon_{\mathrm{r\,eff}}}}\frac{1}{p} \tag{1}$$

where $c$ is the speed of light in vacuum, $p$ is the channel inter-distance, and $\varepsilon_{\mathrm{r\,eff}}$ is the effective dielectric constant.

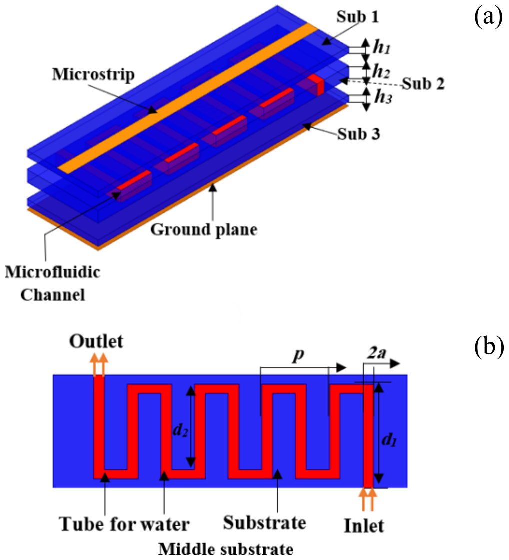


Fig. 1. (a) 3-D structure of the PBG structure for microstrip line. (b) Design parameter of the PBG structure for microstrip.

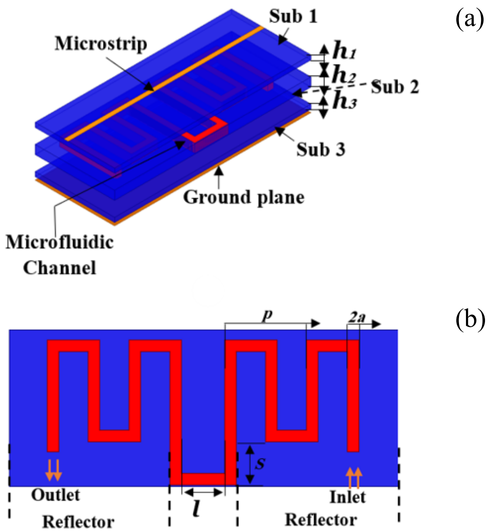


Fig. 2. (a) 3-D structure of the PBG microstrip line sensor. (b) Design parameter of the PBG microstrip line sensor (Sub2).

Since the PBG resonator consists of two reflectors, the resonant frequency is controlled through the two reflectors (center of the band gap of each reflector) so that whenever the center of the band gap for the reflector changes, the resonant frequency of the PBG resonator changes, and since the center of the bandgap changes with the change of the permittivity of water inside the channel, the resonance frequency also changes with the change of the permittivity of water inside the channel.

In our structure, the effective dielectric constant can be estimated as that of the microstrip line with unperturbed ground plane:

$$\varepsilon_{\mathrm{r\,eff}} = \frac{\varepsilon_{\mathrm{r}} + 1}{2} + \frac{\varepsilon_{\mathrm{r}} - 1}{2} \frac{1}{\sqrt{1 + 12\dfrac{h}{w}}} \tag{2}$$

where the dielectric permittivity $\varepsilon_{\mathrm{r}}$ of the proposed structure is determined by the complex permittivity of the substrate and material filled in the channel [17], so, as follows:

$$\varepsilon_{\mathrm{r}} = f_{\mathrm{r}} \varepsilon_{\mathrm{r\,sub}} + (1 - f_{\mathrm{r}}) \varepsilon_{\mathrm{r\,channel}} \tag{3}$$

where $\varepsilon_{\mathrm{r\,channel}}$ is dielectric permittivity of samples filled in the channel, $\varepsilon_{\mathrm{r\,sub}}$ is dielectric permittivity of the main substrate, and $f_{\mathrm{r}}$ is the dielectric filling ratio, given by

$$f_{\mathrm{r}} = a/p \tag{4}$$

Putting Eq. (3) into Eq. (2), we obtain:

$$\varepsilon_{\mathrm{r\,eff}} = \frac{f_{\mathrm{r}} \varepsilon_{\mathrm{r\,sub}} + (1 - f_{\mathrm{r}}) \varepsilon_{\mathrm{r\,channel}} + 1}{2} + \frac{f_{\mathrm{r}} \varepsilon_{\mathrm{r\,sub}} + (1 - f_{\mathrm{r}}) \varepsilon_{\mathrm{r\,channel}} - 1}{2} \frac{1}{\sqrt{1 + 12\dfrac{h}{w}}} \tag{5}$$

As mentioned above, the center of the band gap in the PBG structure depends on several properties, among them the filling ratio between the substrate and the material in the channel. Depending on this property, the basic principle of the proposed sensor is based on the change in the center of the band gap due to the change of the dielectric permittivity inside the channel (Fig. 2). According to relationships (5) and (1), when the channel is filled with a liquid whose dielectric permittivity depends on the temperature, a change occurs in the center frequency of stop band depending on the dielectric permittivity; this variation yields a shift in the resonant characteristics of the PBG microstrip sensor.

The water is the most suited reference liquid in calibration and test measurement, and its dielectric permittivity depends on the change in the temperature and frequency [18]. Based on this characteristic, we will use the change in water permittivity as an indicator of temperature change.

In this work, we will heat the water to different temperatures and fill in the channel with it (Fig. 2). Then we measure the shift in the resonance frequency for the PBG resonator.

A microstrip width of 1.4 mm was used, corresponding to 50 Ω. The unit cell size $p = 8.5$ mm, the value of the radius of the microfluidic channel $a = 1.75$ mm and the length of transmission line $l = 11.2$ mm. With these values, the PBG microstrip structure and resonator are simulated for the centered band gap frequency of 4.55 GHz where the microfluidic channel is filled with water at room temperature and the result is depicted in Fig. 3. This figure shows the transmission coefficient for the PBG microstrip structure and the reflection coefficient for PBG microstrip resonator. Through this figure, the stop band is ranging between 2.9 and 5.9 GHz, which gives an insertion loss higher than 34 dB. For the PBG resonator, it can be seen that the emergence of a transmission peak is in the middle of the band gap.This transmission peak has a resonant frequency of 4.53 GHz, which almost coincides with the center of the stop band.

The shift in the center frequency $\delta f_{\max}$ for the two reflectors can be expressed in terms of the changes in the unit cell size $p$ and the substrate dielectric constant effective $\varepsilon_{\mathrm{r\ eff}}$ as

$$\delta f_{\max} = \frac{\partial f_{\max}}{\partial \varepsilon_{\mathrm{r\ eff}}} \delta \varepsilon_{\mathrm{r\ eff}} + \frac{\partial f_{\max}}{\partial p} \delta p \tag{6}$$

Since the change will be only by filling the water in the microfluidic channel, the unit cell size $p$ can be considered constant so the change $\partial f_{\max}/\partial p = 0$. Hence, the shift in the resonance frequency is only related to the change in the dielectric permittivity of water, which affects the total permittivity of the substrate based on the relationship (5).

Initially, we assume that the reference center frequency $f_0$ is the central frequency of the first band gap when $\varepsilon_{\mathrm{r\ channel}} = \varepsilon_{\mathrm{r\ water}}$ at room temperature ($T_0 = 20°\mathrm{C}$). When

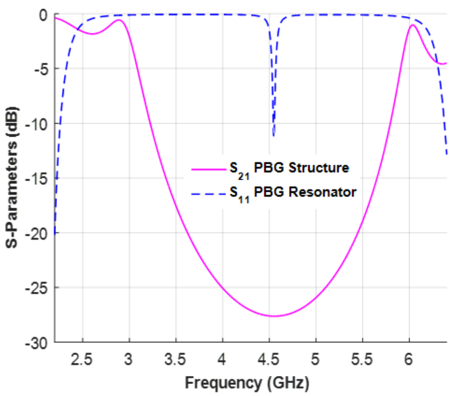


Fig. 3. *S*-parameters of the PBG structure and resonator.

$\varepsilon_{r\ channel}$ is not equal to $\varepsilon_{r\ water}$, the resonance frequency, in this case, it will be a shift to a new frequency by the permittivity effective scaling law as follows [19]:

$$f_T = f_0 \frac{\sqrt{\varepsilon_T - \varepsilon_{sub}}}{\sqrt{\varepsilon_{r\ eff} - \varepsilon_{sub}}} \tag{7}$$

where $f_T$ is the center frequency of the new stop band after the change in the temperature of the water, $f_0$ is the reference central frequency of the stop band when $T = T_0$, $\varepsilon_T$ is the new permittivity effective at temperature $T$. $\varepsilon_{sub}$ is the dielectric permittivity of RT/Duroid 6010, $\varepsilon_{r\ eff}$ is the dielectric permittivity effective calculated by (5) with the reference $\varepsilon_{r\ water} = 68$ at room temperature ($T_0 = 20$°C) [18].

Based on Eq. (1), the relationship between the shifting of the resonance frequency and the change of temperature is given by:

$$\Delta f = f_0 \left( \sqrt{\frac{(\varepsilon_{r\ eff} + K\Delta T) - \varepsilon_{sub}}{\varepsilon_{r\ eff} - \varepsilon_{sub}}} - 1 \right) \tag{8}$$

where $\Delta f$ is the resonance frequency shift, $K$ is the proportional constant of the dielectric permittivity and the temperature change, and $\Delta T$ is the change of temperature of water in °C.

## 3. Results

In the simulation, the substrate used is of RT/Duroid 6010 with dielectric permittivity $\varepsilon_r = 10.2$, loss tangent 0.0023, and copper thickness of 35 μm.

Typically, the temperature dependence of the dielectric permittivity of liquids is described by the thermal coefficient of dielectric constant (TCDk). By using liquids whose dielectric permittivity is temperature-dependent (as water), tunability can be achieved.

To investigate the temperature effect and thermal tenability of the proposed PBG sensor, five different temperatures 20, 28, 33, 42, and 47 were chosen in the simulation.

As mentioned in the above section, the reference effective permittivity dielectric is calculated by (5) with $\varepsilon_{r\ channel} = \varepsilon_{r\ water} = 68$, at the initial temperature $T = T_0$. Figure 4 presents the simulated reflection coefficients of the PBG microstrip sensor for different temperatures.

Since the resonant characteristics of the PBG microstrip sensor relate to the center of the stop band, which, in turn, depends on the permittivity of water filling the channel, we control the process by changing the temperature. The existence of the band gaps and the control of their width in a slab substrate require some conditions on the geometrical and physical parameters, especially as concerns the ratio between the two permittivity's (main substrate and water filled in the microfluidic channel). The frac-

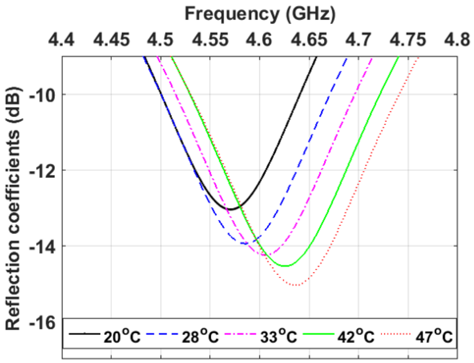


Fig. 4. Simulated reflection parameter $S_{11}$ of the designed sensor for the different temperatures.

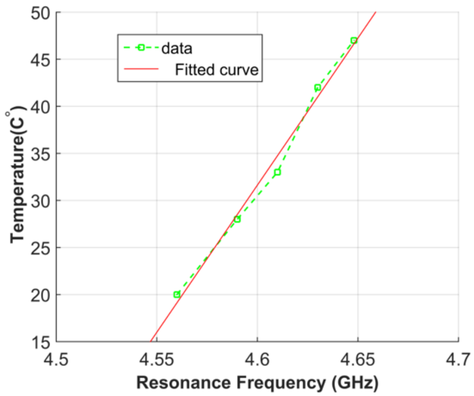


Fig. 5. Different temperatures of water *versus* resonance frequency.

tional bandwidth increases as the permittivity ratio ($\varepsilon_{r\ sub}/\varepsilon_{r\ water}$) increases. Through Fig. 4, it can be seen that the resonance frequency has decreased according to the increasing value of the temperature of water in the channel. For example, in the reference case with a temperature equal to 20°C, the resonance frequency is 4.56 GHz. In the case of 28°C, the resonance frequency is 4.58 GHz, and for 47°C, the resonance frequency drops to 4.64 GHz. Through the simulated results, the resonant frequency is shifting by 80 MHz as the temperature changed from 20 to 47°C. Depending on (8), the resonant frequency is shifting according to $T$ by a linear relationship. Based on the resonance frequency for each temperature, this relationship is presented in Fig. 5. This figure shows the simulated and curve-fitting results. The curve fitting results in an accurate ($r^2 = 0.9951$) linear relation between the temperature and their resonance frequencies as

$$T(f_0) = 312.61 f_0 + 1406.4 \tag{9}$$

Sensitivity is the main performance indicator and can be expressed through:

$$S = \frac{f_{01} - f_{02}}{f_{01}} \frac{1}{\Delta T} \quad [\%] \tag{10}$$

According to the simulated results, the sensitivity increases as the shift of the resonance frequency increases, and the sensitivity of this sensor is $S = 0.18\%$.

## 4. Conclusion

In this paper, a class of sensors using the photonic band gap microstrip resonator is proposed for a temperature change. The PBG microstrip sensor structure consists of two PBG reflectors with a 50 Ω microstrip transmission line that separates them, which acts as a resonant cavity. The sensing principle in this concept is achieved based on the change in the center of the stop band for the two reflectors depending on the change of the temperature of the water filled in the microfluidic channel. This variation gives rise to a change in the resonant frequency of the resonator. A mathematical linear model for resonant frequency shifts due to the variation in the temperature of the water is derived. The proposed PBG microstrip resonator sensor is very simple and low cost for temperature measurements in the industrial applications. The proposed sensor can be also applied to other fields such as humidity sensing as well as the salinity determination.

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