Wavelength tunable TFBG based microwave sensor using surface plasmon resonance

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Wavelength tunable TFBG based microwave sensor using surface plasmon resonance

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Abstract A noble idea is used to propose a wavelength tunable tilted Fiber Bragg Gratings based microwave sensor using surface plasmon resonance. The Bragg wavelength shifts linearly about 6 pm/°C, due to the temperature change. This temperature variation occurs because of the microwave–metal interaction at cladding layer of the optical fiber based proposed sensor. The wavelength tuning can be achieved by using tilted Fiber Bragg Gratings. To use the wavelength sources of 850 nm, 1310 nm and 1550 nm, tilted Fiber Bragg Gratings with grating periods of 293.65 nm, 452.56 nm and 535.47 nm respectively are required in the same fiber with certain distances among them.

1. Introduction

Optical fiber (OF) can be used as a sensor when it is specially designed. Design of an optical fiber for sensor application is done in such a way, so that a short portion of the fiber’s refractive index differs from the usual fiber core and cladding refractive index (Udd, 1991; Sharma et al., 2007; Marazuela and Moreno-Bondi, 2002). One of the techniques is to introduce Fiber Bragg Gratings (FBGs) in the fiber core. Fiber Bragg Grating is a periodic wavelength scale variation of refractive index, inscribed in the segment of the Fiber core. Bragg grating reflects the light at a particular wavelength which satisfies the Bragg condition. This reflection in a grating occurs as coupling between forward and backward propagation modes at a certain wavelength. The coupling coefficient of the modes is maximal when a special condition (Bragg condition) between wave vectors of light and vector number of the grating is satisfied (Hill and Meltz, 1997):

\[ n_{\text{eff}} \cdot \lambda_B = 2 \cdot m \cdot \Lambda \]  

where \( \lambda_B \) is the wavelength of light called Bragg wavelength, \( \Lambda \) is grating period, \( n_{\text{eff}} \) is effective refractive index of the core and \( m \) is the diffraction order.

For a single FBG, theoretically there exists infinite number of Bragg wavelengths. It can be clearly seen from (1), as for different values of \( m \), i.e. diffraction order of Bragg wavelength are different. These Bragg wavelengths are separated from each other by quite a large spectral range, so on practice, only one (first or sometimes second) Bragg resonance wavelength is being used. For instance, when the first Bragg wavelength of the grating (\( m = 1 \)) is 1550 nm, then the second one is twice
less, i.e. 750 nm, while the spectral range of sources used for Fibers usually doesn’t exceed 100 nm.

Additional Bragg peaks can occur if the modulation of the refractive index in FBG is not sinusoidal (which is usually the case) even though most of the gratings inscribed in Fiber have nearly sinusoidal index modulation.

It is possible to make the FBG in the core of the fiber with some tilting angle. This type of FBG is known as Tilted Fiber Bragg Grating (TFBG) Shevchenko and Albert, 2007. Here, the variation of the refractive index occurs at an angle to the optical axis. The reflected wavelength and bandwidth of the TFBG is dependent on the tilting angle.

If a FBG’s period is varied, such as a linear variation in the grating period results chirp. This new type of FBG is known as Chirped Fiber Bragg Gratings (CFBGs). This CFBG has special characteristic, the reflected wavelength changes with respect to the change in grating period. This unique feature is used for many applications (Li et al., 2009). If the tilting is applied in case of CFBG, then Tilted Chirped Fiber Bragg Gratings will be created. This paper outlines the use of this TCFBG concept with surface plasmon resonance (SPR) to detect microwaves (MW). Now a days SPR based optical fiber is vastly used for sensing applications (Sharma et al., 2009; Slavik et al., 2001; Piliarik et al., 2003; Monzon-Hernandez et al., 2004; Homola, 2003; Willets and Van Duyne, 2007; Shao et al., 2010; Iga et al., 2005; Sharma and Gupta, 2006; Spacikova et al., 2009).

2. Surface plasmons

A conductor, such as metal has a lot of free electrons. The electrons inside the metal can be considered as plasma particles. Equal numbers of positive charged ions from lattice are also present inside the conductor. So, the total charge density in the conductor is zero. When an external field is applied these electrons will start to move. The electrons will move toward the positive region and at the same time the positive ions will move opposite to the electrons. Due to this moving mechanism a longitudinal oscillation will be introduced in the conductor which is known as the plasma oscillation (Willets and Van Duyne, 2007).

A conductor and a dielectric are required to support the surface plasma to oscillate at its interface. In general, a metal and dielectric interface is used to support the surface plasmon oscillation. Due to this oscillation, a surface plasmon wave is generated. This surface plasmon is only TM polarized electromagnetic field because there is no solution of the Maxwell’s equation for TE polarized case. This wave is decayed exponentially in the metal. Surface Plasmon Wave (SPW) is characterized by:

$$\beta = \frac{\alpha}{c} \sqrt{\varepsilon_M \varepsilon_D \varepsilon_0}$$  \hspace{1cm} (2)

where, $\beta$ is the propagation constant, $\alpha$ is the angular frequency, $c$ is the speed of light in vacuum, $\varepsilon_M$ and $\varepsilon_D$ are the permittivities for metal and dielectric respectively.

It can be seen from (2) that the property of the SPW is dependent on the property of the two materials i.e. the metal and dielectric media. To create the surface plasmon oscillation it is necessary to excite the electrons in the conductor by impinging EM field (light) on the surface. The electrical permittivity for the conductor (metal) is negative and the electrical permittivity for the dielectric is positive. In the dielectric medium the propagation constant (maximum) can be written as:

$$\beta = \frac{\alpha}{c} \sqrt{\varepsilon_M}$$  \hspace{1cm} (3)

where, $\varepsilon_M$ is the permittivity of SPW. The propagation constant for surface plasmon wave is higher than the propagation constant of light in the dielectric medium. As a result, it is not possible excite the surface plasmon with normal light; thus it is required to use the light with extra momentum or energy with same polarization state as the surface plasmon wave. Moreover, the propagation constant should be matched with the surface plasmon wave.

2.1. SPR based TFBG sensors

Based on the SPR principle, recently TFBG is used as a sensor (Shevchenko and Albert, 2007). For this sensor application the cladding of the fiber was removed and a metal film was deposited (either gold or silver), so that the surface plasmon can exist at the interface of the metal–dielectric as reported in Willets and Van Duyne (2007). Here, the guided mode can couple to cladding mode as the Bragg grating is tilted with a certain angle. As a result it can excite the surface plasmon waves. The phase matching condition is fulfilled for the surface plasmon waves by proper tilting of the Fiber Bragg Grating (FBG).

3. Microwave metal interaction

The depth of penetration of MW in metal is in the order of nanometers; normally MW frequency is reflected from the bulk metal surface. So there is almost no effect of the MW for a bulk metal. But MW has a great impact on thin film of nanometers; normally MW frequency is reflected from the bulk metal surface. So there is almost no effect of the MW for a bulk metal. But MW has a great impact on thin film of nanometers. MW can penetrate the metal up to few nanometers range. As MW is an electromagnetic wave, when it propagates inside the metal film there will be eddy current creation which results in heating inside the metal film.

Generally, a thin metal film is used at the cladding layer of the optical fiber so that a metal–dielectric (cladding) interface is created to support the surface plasmon wave for SPR based optical fiber sensor applications. Thickness of the metal film should be in nanometer range. So, microwave can interact easily with this metal film. For this type of sensor applications, gold, silver or sometimes metal alloy are used. Like other electromagnetic waves MW has also two components – H field and E field. The heat response of H field component is much more comparing with the E field heating. One over four times less power is required for heating with MW of H field than the E field as reported in Yoshiwaka (2010).

4. TFBG based microwave sensor

For the TFBG based sensor the wavelength source was fixed (Shevchenko and Albert, 2007). There was no flexibility to use different sources for the same sensor. In this study, a concept of SPR based OF sensor to detect MW with flexible reference wavelength source is proposed. At the same time the concept of Tilted Chirped Fiber Bragg Grating (TCFBG) is
also used to get this flexibility. The flowchart of the proposed sensor’s sensing scheme is shown in Fig. 1.

More than one TFBG will be used in the fiber with different grating periods (i.e. TCFBG) to get the flexibility. The tilting will be done so that the reflected mode becomes the cladding mode. Thus it excites the surface plasmon wave. As an example if it is required to use 850 nm, 1310 nm and 1550 nm as the wavelength, then about 0.001, so the sensitivity is:

\[
S = \frac{\lambda_2 - \lambda_1}{\Delta T_{\text{eff}}} = \frac{0.117}{13.31} = 0.0089 + \Delta S_{\text{err}}
\]

where, the errors from the difference can be calculated from absolute errors by:

\[
\Delta \lambda_B = 2 \cdot (n_{\text{eff}} + \Delta n_{\text{eff}}) \cdot (\Lambda + \Delta \Lambda)
\]

After simplifying the expression it will result in:

\[
\Delta \lambda_B = 2(n_{\text{eff}} \cdot \Lambda + \Delta n_{\text{eff}} \cdot \Delta \Lambda + \Delta n_{\text{eff}} \cdot \Delta \Lambda)
\]

The last term at the right hand side of (5) can be neglected as it is multiplication of two small quantities. Also taking into account (4) i.e. unperturbed Bragg condition, it will be the formula for the shift of Bragg wavelength:

\[
\Delta \lambda_B = 2(n_{\text{eff}} \cdot \Lambda + \Delta n_{\text{eff}})
\]

A current source was used in the lab to heat the panel where the CFBG was attached. The current was increased from 0 A to 0.8 A which results in temperature increase of the panel from 27.7 °C to 54.6 °C respectively. Due to the temperature change there is a related wavelength shift which is listed in Table 1. This result is plotted in Fig. 4.

In Fig. 4, linear fitting performed by MATLAB is presented together with experimentally obtained curve of Bragg wavelength dependence on temperature. The sensitivity according to this fitting is 7.44 pm/°C.

If more attention is paid to the experimental curve, it can be seen that in the beginning, the measurements weren’t performed appropriately, as in this region the dependence is not linear. Additionally a well linear region was observed starting from temperature 42 to 55 °C. The results of sensitivity was calculated only for that region and found as 8.9 pm/°C.

From the above result it is clear that the temperature response for the CFBG is linear same as the FBG for a specific wavelength. This result can be compared with that of (Khan, 2012). From the experimental result it can be seen that there is an average 6 pm wavelength shift due to 1 °C temperature change.

4.2. Calculation of error

For the calculation of the error let us consider the measurements of Sl. No. 12 and 18 (see Table 2).

The absolute error of the temperature is 0.1 °C and for wavelength 0.001, so the sensitivity is:

\[
S = \frac{0.117}{13.31} = 0.0089 + \Delta S_{\text{err}}
\]
The error coming from the ratio can be calculated in the following way:

\[
\Delta S_{err} = S \cdot \sqrt{\left( \frac{\Delta \lambda_{err}}{\Delta \lambda} \right)^2 + \left( \frac{\Delta T_{err}}{\Delta T} \right)^2}
\]

\[
= 0.0089 \cdot \sqrt{\left( \frac{0.014}{0.117} \right)^2 + \left( \frac{0.14}{13.1} \right)^2}
\]

\[
= 0.0089 \cdot 0.016 = 0.00014 \text{nm/°C}
\]

The sensitivity of the sensor with the calculated error is:

\[
(8.9 \pm 0.14) \text{pm/°C}
\]

5. Efficient design consideration

Fig. 5 shows a chirped grating with length \( L_g \) and chirped Bandwidth (BW) \( \Delta \lambda_{chirp} \). This BW is related as (Kashyap, 1999):

\[
\Delta \lambda_{chirp} = 2n_{eff}(\Lambda_{long} - \Lambda_{short})
\]

\[
= 2n_{eff}\Delta \lambda_{chirp}
\]

The phase matching condition for the grating is defined by (1). The number of steps that will be in a chirped grating can be formulated as:

\[
\Delta \lambda_{diff} = \sqrt{\left( \Delta \lambda_{err} \right)^2 + \left( \Delta \lambda_{corr} \right)^2}
\]

\[
= \sqrt{2(\Delta \lambda_{err})^2} = \sqrt{2(0.001)^2} = 0.0014
\]

\[
\Delta T_{diff} = \sqrt{\left( \Delta T_{err} \right)^2 + \left( \Delta T_{corr} \right)^2}
\]

\[
= \sqrt{2(\Delta T_{err})^2} = \sqrt{2(0.1)^2} = 0.14
\]
where $\lambda_{\text{Bragg}}$ is the central Bragg wavelength of the grating.

Using $L_g = 100$ mm, $\Delta \lambda_{\text{chirp}} = 0.75$ nm & Bragg wavelength 1550 nm in Kashyap (1999) 200 sections were found with 2 steps/mm and then next 42 steps was used with 0.42 steps/mm. It was reported that if the sections of the grating are varied from lower to higher or vice versa the reflectivity characteristics remain approximately the same.

There are several conditions that need to be considered to get TCFBG. The coupling condition for this case is (Spacková et al., 2009):

$$\lambda_{\text{resonance}}^i = \frac{n_{\text{core}}^i \Lambda_{\text{eff}} + n_{\text{cladding}}^i \Lambda_{\text{eff}}}{\Lambda_{\text{Bragg}}} \Lambda_g$$  \hspace{1cm} (15)

where $\lambda_{\text{Bragg}}$ is the central Bragg wavelength of the grating. Using $L_g = 100$ mm, $\Delta \lambda_{\text{chirp}} = 0.75$ nm & Bragg wavelength 1550 nm in Kashyap (1999) 200 sections were found with 2 steps/mm and then next 42 steps was used with 0.42 steps/mm. It was reported that if the sections of the grating are varied from lower to higher or vice versa the reflectivity characteristics remain approximately the same.

If three TFBGs are used in the same fiber then it will have three reflected wavelengths which can excite the surface plasmon (SP). This results in wavelength flexibility. It can be compared with the result of Spacková (2009) for the first FBG, the SP-resonance wavelength was found approximately at 0.77 $\mu$m but for the second FBG, with a different period the SP-resonance wavelength was approximately at 0.81 $\mu$m. So, by using chirped FBG, i.e. FBG with a different period, the SP waves can be excited and resonance occurred with different wavelengths. The sensor characteristic also depends on the refractive index change, FBG length variation and width of the gold film as indicated by Sharma and Gupta (2006), Iga et al., 2005, (Suzuki et al., 2008).

6. Conclusion

Tilted Fiber Bragg Grating based new MW sensor is proposed. MW detection possibility was analyzed based on surface plasmon resonance. Thickness of metal film and polarization dependency affects the SPR wave, so the design needs an optimization. MW range that can be detected by this sensor depends on the metal film layer thickness and the type of metal used for the generation of SPR. The analysis was done considering the SPR generation, polarization, Bragg wavelength shift, metal film thickness, corresponding temperature effects or thermo-optic effect. Factors those were not considered in this analysis: power or energy of the MW frequency, amplitude of the MW frequencies, and different bands of MW frequencies. It may be possible to have an effect of high power/energy MW frequency and low power/energy MW frequency on the sensor.

![Figure 4](image-url) Bragg wavelength dependence on temperature and linear fitting.

Table 2 Experimental data for error calculation.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Temperature (°C)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>41.5</td>
<td>1583.385</td>
</tr>
<tr>
<td>18</td>
<td>54.6</td>
<td>1583.502</td>
</tr>
</tbody>
</table>

![Figure 5](image-url) Chirped grating.

$$T = \frac{2n_{\text{eff}} \Delta \lambda_{\text{chirp}}}{\pi \lambda_{\text{Bragg}}}$$  \hspace{1cm} (14)
The manufacturing cost of this sensor will be the main limitation. On the contrary the proposed sensor will be very small so, integration is possible with other electronics.

Conflict of interest

The authors declare no conflict of interest.

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