Planar Waveguide Bragg Grating Pressure Sensor—Design and Applications

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Abstract We design and simulate the waveguide Bragg grating pressure sensor on Boro float glass substrate. Rib waveguide structure is used for the design of pressure sensor, centered at 632.8 nm. The pressure sensor is simulated for a range from 5 to 80 MPa. Poly(methyl methacrylate) is used as the waveguiding material and air as the cladding surface. The rib waveguide is designed in RSoft tool using beam propagation method, and GratingMOD is used to create periodic perturbations on it. The pressure sensitivity as observed after simulation is 0.074 nm/MPa.

Keywords Waveguide Bragg grating · Pressure sensor · Rib waveguide · Poly(methyl methacrylate)

1 Introduction

An optical waveguide is being designed for many applications such as medical assistance, communication and hydraulics. The sensor is designed for the unique needs of extreme endurance, high-power hydraulic cylinders and accumulators, such as those used in offshore oilfield mining and drilling operations or heavy-duty construction, pipeline pressure measurement, oil reservoir monitoring, radar applications, downhole pressure monitoring and military vehicles. An optical integrated circuit is a thin film type optical circuit designed to perform a specific function by integrating optical waveguides and other functional components all on a single substrate. The basic structures of optical waveguide consist of core and clad. In a nonplanar waveguide, the core is surrounded by the cladding in all transverse directions. For device applications, extensively used waveguide is the nonplanar waveguides [1]. We use rib waveguide for this design and its structure is shown in Fig. 1.

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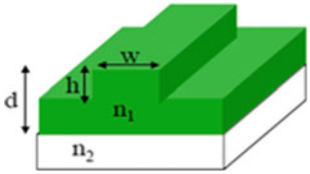
Fig. 1 Rib waveguide



2 Theory

2.1 Fiber Bragg Grating Principle

In principle, the FBG reflects particular wavelengths of light near Bragg resonance and the rest of the spectrum is being transmitted.

Figure 2 shows the core of a single-mode fiber exposed to periodic pattern of intense ultraviolet light. A permanent increase in refractive index of the core is produced by the exposure, creating a fixed periodic grating. A small amount of light is reflected at each periodic refraction change.

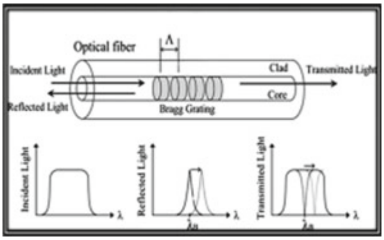
When the grating period is approximately half the input light's wavelength, all the reflected light signals combine coherently to one large reflection at a particular wavelength. This is known as the Bragg condition, and the wavelength at which this reflection occurs is called the Bragg wavelength. Wavelengths that satisfy the Bragg condition are affected and strongly back-reflected. The reflected component's central wavelength satisfies the Bragg relation:

$$\lambda_{ref1} = 2 \times n \times \Lambda \tag{1}$$

where n is the refractive index of the core, and Λ is the grating period.

Since n and Λ are temperature and strain dependent, as temperature and strain vary, the wavelength of the reflected component will shift by a particular value proportional to the temperature/strain.

Fig. 2 Fiber Bragg grating principle



2.2 Waveguide Bragg Grating Principle

The optical waveguide consists of core, clad and substrate. The materials used in our work are PMMA, air and Boro float glass, respectively.

Bragg grating is an optical waveguide formed by creating periodic perturbations or refractive index modulation. Light is made to propagate through the core. A particular wavelength, that is, the centre wavelength will be reflected due to the presence of grating [2].

When there is an application of pressure there is a shift in the wavelength of light. This shift in wavelength is calculated using the Bragg's law,

$$\lambda_{new} = 2 \times n \times \Lambda \tag{2}$$

2.3 Materials Used for the Design

PMMA. Poly(methyl methacrylate) or poly(methyl 2-methylpropenoate) is the polymer of methyl methacrylate, with chemical formula $(C_5H_8O_2)_n$. It is also known as acrylic glass or simply acrylic.

Properties of PMMA materials. PMMA is a linear thermoplastic polymer. PMMA has high Young's modulus, high mechanical strength and low elongation at break. It does not shatter on rupture. It is one of the hardest thermoplastics and is also highly scratch-resistant. It exhibits good water-absorbing capacity and low moisture, due to which products produced have good dimensional stability. As the temperature rises, both of these characteristics increase.

Why PMMA material. Due to low cost, ease of fabrication and assembly, and compatibility with other materials, polymer materials provide a potent alternative to conventional optical materials. One of the important characteristic of polymeric optical materials is their relatively high light absorption rates, at approximately 0.2 dB/cm, as compared to 0.2 dB/km for glass fibers at wavelengths of 1550 nm.

3 Design of Waveguide

3.1 Rib Structure

In multimode waveguides that support more than two guided modes, power gets distributed to the clad and substrate regions causing losses. To avoid this, most waveguide devices consist of single-mode 3D waveguides [3].

Rib waveguide is a waveguide in which the guiding layer basically consists of the slab with a strip superimposed onto it. Rib waveguides provide confinement of the wave in two dimensions. The optical losses are lower for rib waveguides than for strip ones. For the simulation of the rib waveguide, the following parameters were considered:

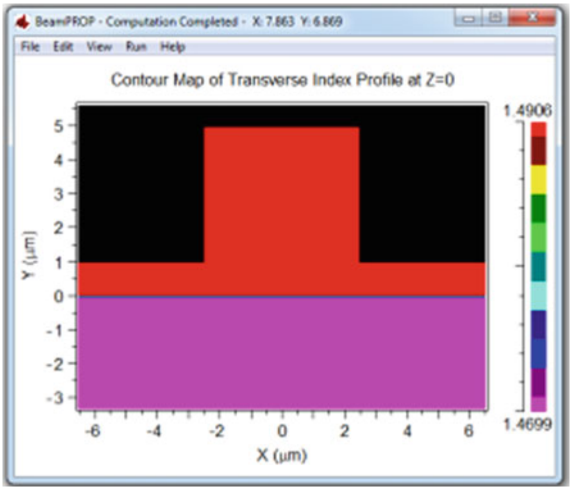
a. Waveguide model dimension: 3D
b. Simulation tool: BeamPROP
c. 3D structure type: Rib
d. Free space wavelength: 632.8 nm
e. Background index: 1.4699
f. Index difference: 0.0207
g. Waveguide width: 5 μm
h. Waveguide height: 5 μm
i. Profile type: Step-index

The background index is the refractive index of the substrate and the index difference is the difference between the refractive index of the core and the substrate.

3.2 RI Profile

A refractive index profile is the distribution of **refractive indices** of materials within an **optical waveguide** [4]. It signifies the light distribution in the optical fiber. Figure 3 shows the RI profile in which the low index value indicates the refractive index of the substrate and the high index value indicates the refractive index of the core.

Fig. 3 RI profile of the rib waveguide



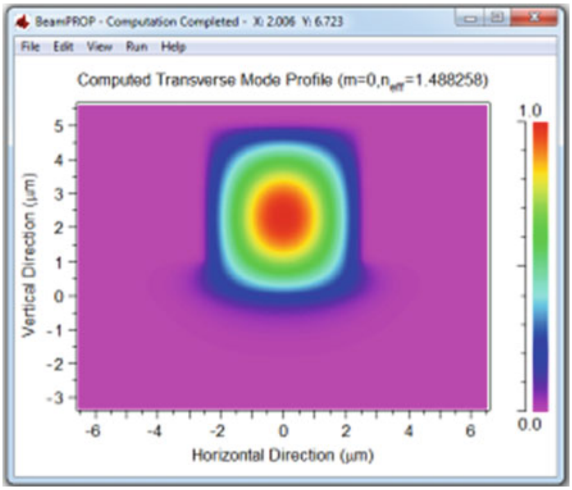


Fig. 4 Mode profile in the rib waveguide

3.3 *Mode Profile*

The mode profile represents the light confinement in different regions of the waveguide. Figure 4 shows the mode profile in the rib waveguide.

3.4 *Principle of Pressure Sensing*

The effective index of refraction and the periodicity of the grating determine its center wavelength. When the pressure is applied, the grating period changes and hence wavelength shifts according to the Bragg's condition given by Eq. (2) (Tables 1 and 2).

Table 1 Comparison of analytical and practical values of wavelengths

Pressure (in MPa)	Pressure sensing $E_{ps} = \frac{p\times[1-[2\times\nu]]}{E}$	$\lambda_{new} = \Delta\lambda + \lambda_c$ in μm	λ RSoft in μm
5	0.653061×10^{-3}	0.6331701	0.635
7	0.9142857×10^{-3}	0.63331825	0.6351
10	1.3061224×10^{-3}	0.63354036	0.6353
15	$1.959183673 \times 10^{-3}$	0.63391055	0.6357
20	$2.6122448898 \times 10^{-3}$	0.6342807	0.6361
40	5.2244897×10^{-3}	0.6357614	0.6376
60	7.836734×10^{-3}	0.6372421	0.639
80	10.44897×10^{-3}	0.6387229	0.6405

Table 2 Comparison of effective refractive index values by analytical method and RSoft tool

Waveguide width (μm)	n_{eff} Analytical method	n_{eff} RSoft
2	1.47200	1.482553
4	1.48900	1.487608
6	1.49013	1.488621
8	1.49038	1.488992
10	1.49048	1.489167

$$\lambda_{new} = 2 \times n \times \Lambda \tag{3}$$

Pressure sensing equation by analytical method:
Poisson ratio, $\nu = 0.34$
Strain optic coefficients: $P_{11} = 0.3$; $P_{12} = 0.297$
Effective index of refraction, $n_{eff} = 1.489$
Young's modulus, $E = 2.45$ GPa
Pressure sensing equation,

$$E_{ps} = pressure \times \left[\frac{(1 - 2 \times \nu)}{E}\right] \tag{4}$$

Strain optic constant,

$$P_E = \frac{n_{eff}^2}{2} \times [P_{12} - (\nu \times \{P_{11} + P_{12}\})] \tag{5}$$

Shift in wavelength:

$$\Delta\lambda_B = \lambda \times (1 - P_E) \times E_{ps} \tag{6}$$

$$\lambda_{new} = centerwavelength + \Delta\lambda_B \tag{7}$$

4 Result and Discussions

Table 3 shows the sensitivity of different FBG pressure sensors with different center wavelengths.

On collation of Figs. 5, 6 and 7, the shift in wavelength spotted identical.

Figures 8 and 9 illustrate that pitch period and shift in wavelength vary linearly with pressure applied.

Figure 10 outlines the rise in waveguide width and the rise in effective RI. From

Table 3 Summary of FBG pressure sensors in order of sensitivity [5]

Sensitivity	Range	Wavelength	FBG type novelty
3 pm/MPa	70 MPa	–	Standard/bare
7 nm/MPa	–	–	Standard/diaphragm
1.57 pm/kPa	0–1 MPa	–	Standard/diaphragm
51 pm/MPa	–	–	Long period grating
265 pm/kPa	–	–	Photonic crystal fiber
28 nm/MPa	–	–	Standard/temperature insensitive
0.116 nm/kPa	15 kPa	1550 nm	Standard/rubber diaphragm
1.32 pm/kPa	–	–	Polymer fiber/vinal diaphragm

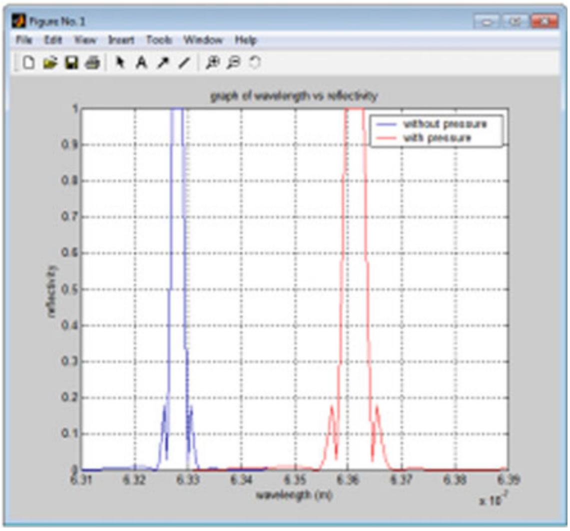


Fig. 5 Plot of maximum reflectivity as function of wavelength (MATLAB)

6 µm RI becomes constant. Thus optimization of waveguide width dimensions is achieved.

Fig. 6 Grating spectral response with apodization (RSoft)

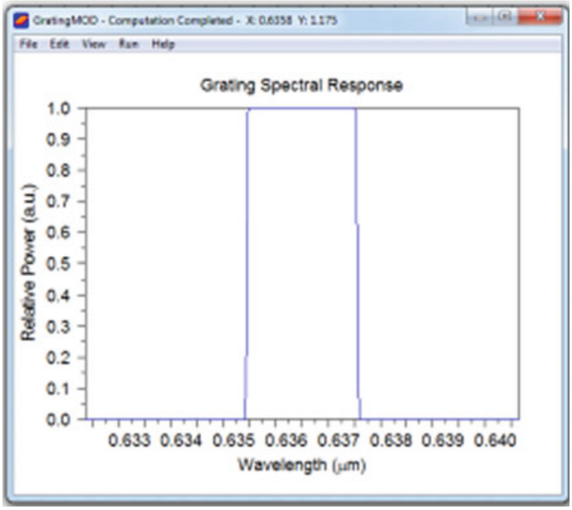


Fig. 7 Grating spectral response without apodization (RSoft)

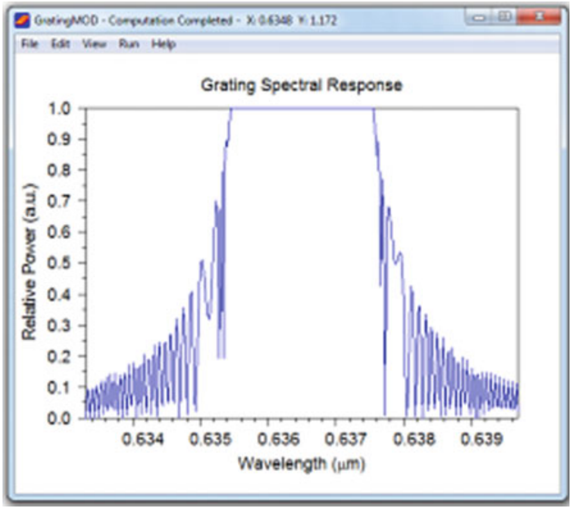


Fig. 8 Plot of pitch period and wavelength as function of pressure

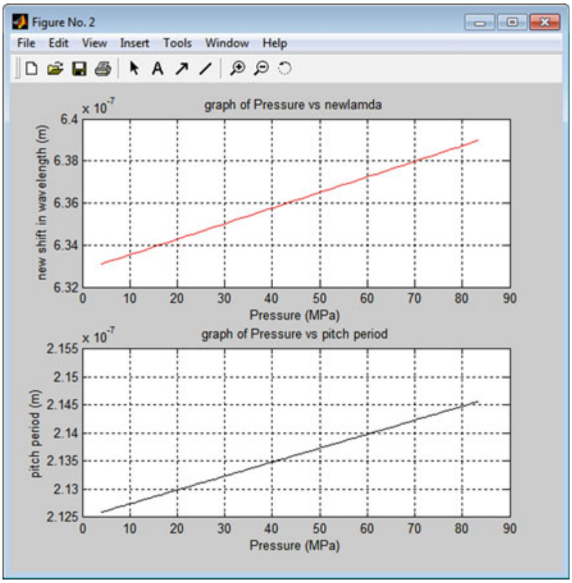
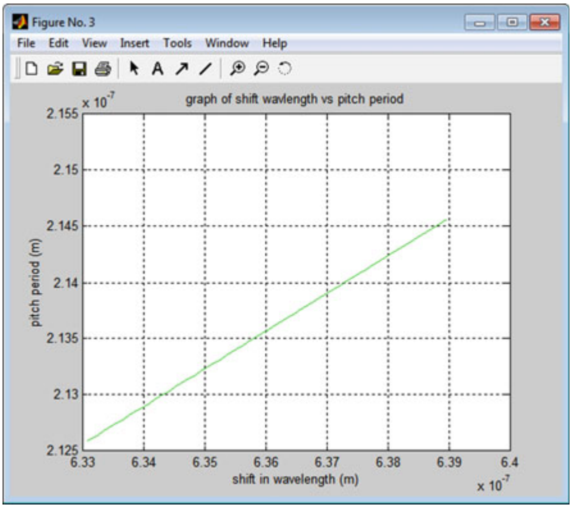


Fig. 9 Plot of pitch period as function of new shift in wavelength



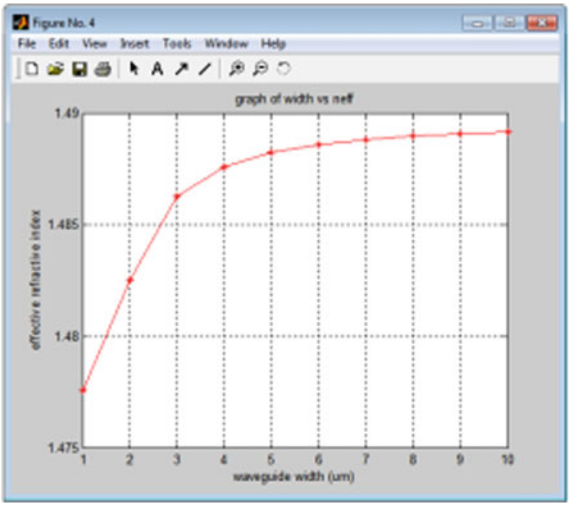


Fig. 10 Plot of effective refractive index as function of waveguide width

5 Conclusion

The waveguide Bragg grating sensor has been designed and simulated in this work. The sensor is observed to have the sensitivity of 0.074 nm/MPa. This sensor can be used for hydraulic applications. The sensor can be further used for similar kind of pressure-sensing applications in industries.

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