A Novel Color Sensor Based on Uniform Fiber Bragg Gratings

Detection Capability of Multiple Colors by FBG

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***Abstract*—In this paper, a fiber Bragg grating (FBG) based color sensor is proposed. A theoretical model is investigated for FBG with a view to evaluating the visible spectrum and a practical prototype is envisaged. Finally, the novel approach is presented to utilize it as a color sensor for multi-dimensional applications such as robotic gesture in tracking path, finding objects and other industrial purposes.**

Keywords—FBG; coupled mode theory; color sensor; electromagnetic spectrum

I. INTRODUCTION

As an essential wave guiding medium or light pipe, optical fiber plays significant role in optical communications, optoelectronics and sensors. Innovations in optical fiber technology are revolutionizing world communications. A new type of microstructure inscribed in the optical fibers, i.e., fiber Bragg gratings (FBGs), has received considerable attention in recent years. FBG is a periodic structure fabricated inside the core of a photosensitive optical fiber. The periodicity can be mechanical like variation of the core diameter or it can be optical like variation of the refractive index of the core. In FBG, two identical counter propagating modes get coupled and the energy is transferred from the forward traveling to the backward traveling mode. Consequently, we get reflection of the modal energy which is strongly wavelength dependent. The FBG, therefore, reflects certain wavelengths keeping propagation of other wavelengths practically un-affected.

The physical mechanism of inscribing the Bragg grating in a fiber is the photosensitivity of the fiber core. When a germanium-doped (GeO_2-doped) fiber is exposed to a high-intensity UV light, the refractive index of the fiber core is permanently changed. In 1978, Hill et al. [1] first reported the photosensitivity phenomenon in optical fibers achieved by the interference between counter-propagating waves inside the fiber core. A decade later, Meltz et al. [2] obtained the first FBG which was imprinted in Ge-doped silica single mode fiber by transverse coherent 244 nm UV beams.Since then, FBG has become a potential optical device in a wide range of optical communication and sensing applications [3]-[5]. Particularly FBG has emerged as a popular sensor due its salient features in the sensing technique [6]-[7].The FBG sensors exceed other conventional electric sensors in many aspects, for instance, immunity to electromagnetic interference, compact size, light weight, flexibility, stability, high temperature tolerance and resistive to harsh environment. Due to their several distinguished advantages, FBG based sensors have found their various applicationsin the measurement of numerous physical parameters including temperature, strain, pressure, vibration, curvature, displacement, load and ambient refractive index [8]-[9].

In this paper, we have proposed a novel approach to use a uniform FBG as a color sensor based on its unique sensing mechanism. Various grating periods are calculated to characterize it.

II. THEORETICAL ANALYSIS

Coupled mode theory [10] is required to theoretically predict the spectral dependence of FBG and reflectivity. Coupled mode equations describe forward and backward propagating waves (both amplitude and phase) as they are confined within the fiber's grating region. The initial assumption is that the index modulation follows a raised-cosine pattern, where the index along the fiber can be expressed as:

$$n(z) = \Delta n \cos\left(\frac{2\pi z}{\Lambda}\right) \quad (1)$$

Here Δn is the peak change in refractive index and Λ is the spatial period. According to the mode coupling phenomenon the two modes show strong coupling as:

$$\beta_1 - \beta_2 = \frac{2\pi m}{\lambda} \quad (2)$$

This is called the Bragg condition. Here, β_1 and β_2 are the phase constants of the forward and backward propagating modes, respectively and m is an integer which defines the diffraction order. If the effective refractive index is η_{eff}, then

$$\beta_1 = \frac{2\pi\eta_{eff}}{\lambda} \quad (3)$$

Now if we take two identical counter propagating modes, $\beta_1 = -\beta_2$. Thus the Bragg condition gives the wavelength which is strongly reflected by the grating as

$$\lambda_{Bragg} = 2\eta_{eff}\Lambda \quad (4)$$

This is called the Bragg wavelength. The important thing to note here is that the period of the refractive index variation is of the order of the wavelength to be reflected. In optical communication since the wavelengths lie in the range of 1-2μm, the grating period has to be of the same order. The fabrication of FBG therefore is little difficult, however once the grating is made, it offers very stable performance. The grating structure can be uniform or graded, apodized, chirped, tilted and superstructure. The schematic of a uniform FBG is shown in Fig. 1.

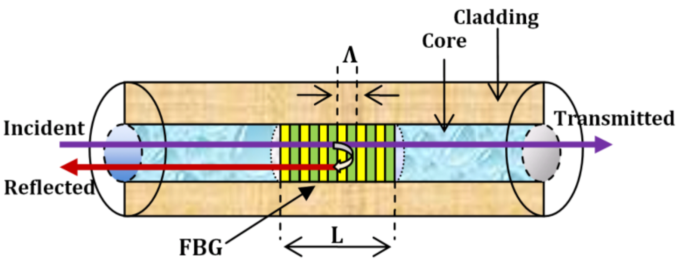

Fig. 1.Schematic of a uniform FBG

Here uniform FBG means it has constant period and constant peak amplitude of the refractive index variation throughout the length of the FBG. Let there be two identical modes propagating in opposite directions. Let F denote the amplitude of the forward mode and B denote the amplitude of the backward mode. The required coupled mode equations are given by

$$dF/dz = i\upsilon F(z) + i\kappa B(z) \tag{5}$$

$$dB/dz = -i\upsilon B(z) - i\kappa^{*} F(z) \tag{6}$$

Solving these equations for a uniform grating the reflectivity is given by [11]

$$R\,(L,\lambda)= \frac{\sinh^2[(\sqrt{\kappa^2-\upsilon^2})L]}{\cosh^2[(\sqrt{\kappa^2-\upsilon^2})L]-\frac{\upsilon^2}{\kappa^2}} \tag{7}$$

Here,

L= Total length of grating

κ = AC coupling coefficient, given by $\kappa = \frac{\pi\nu\Delta n}{\lambda}$ and

ν= Fringing visibility

υ= General self-coupling coefficient, given by

$$\upsilon = \delta + \sigma - \frac{1}{2}\frac{d\varphi}{dz}$$

δ= Wave vector detuning, given by

$$\delta = 2\pi\eta_{eff}\left(\frac{1}{\lambda} - \frac{1}{\lambda_{design}}\right)$$

σ = DC coupling coefficient, given by $\sigma = \frac{2\pi\Delta n}{\lambda}$

$\frac{1}{2}\frac{d\varphi}{dz}$ = Chirp component

III. DESIGN OF PROPOSED SENSOR

From the theoretical model of FBG, it is obvious that reflectivity depends mainly on its length and effective refractive index perturbation. If any of these parameters are varied,Bragg wavelength is shifted accordingly. We know that our eyes are sensitive to light which lies in a very small region of the electromagnetic spectrum labeled "visible light". This "visible light" corresponds to a wavelength range of 400 - 700 nm and a color range of violet through red.To get the desired reflective spectrumof an FBG for a particular color, the specifications are needed to be well-defined.The common parameters are chosen as given in Table I.

TABLE I. SYSTEM PARAMETERS

Quantities	Values
Δn	0.0001
L	0.005m
η_{eff}	1.4555
$d\varphi/dz$	0
ν	1

For detecting the exact color,the grating periods are designed following (4) which are listed below in Table II.

TABLE II. GRATING PERIODS FOR COLORS

Colors	Grating Period (μm)
Violet	0.1374
Indigo	0.1528
Blue	0.1623
Green	0.1821
Yellow	0.1992
Orange	0.2078
Red	0.23358

Following Table I and Table II the overall spectrum is shown in Fig. 2 and the spectrum of individual color is found in Fig. 3 based on (7).All the plots were done in MATLAB R2009a.

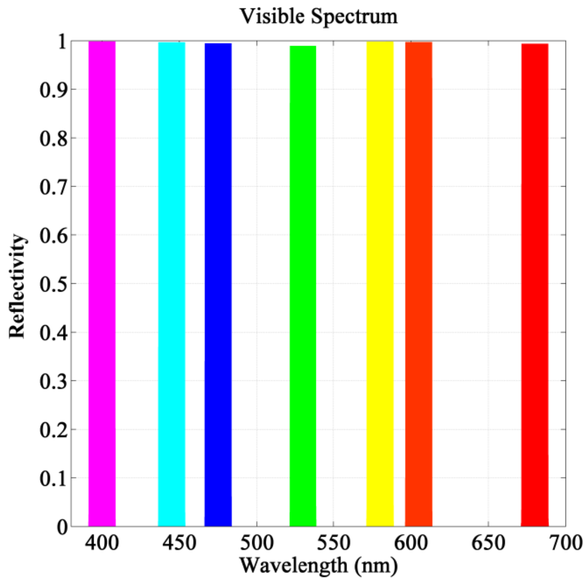

Fig. 2.Overall spectrum of seven colors

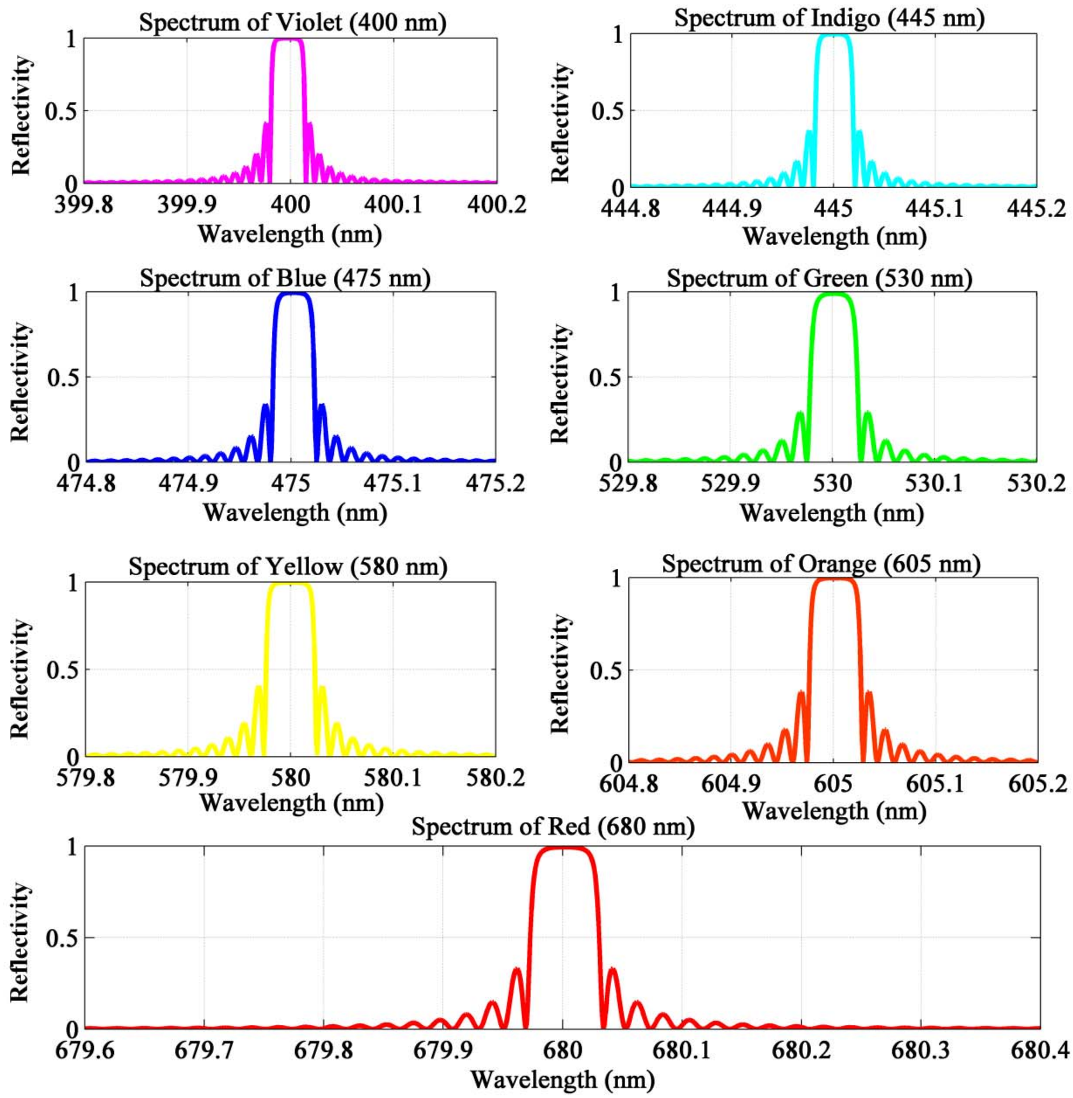

Fig. 3.Reflective spectrum of individual color

Now it is required to implement a detection method. For this purpose, the block diagram of the desired sensor system can be proposed as given in Fig. 4.

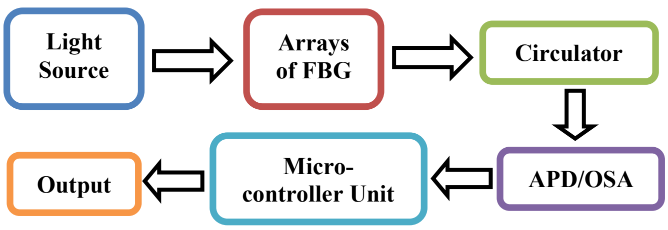

Fig. 4.Block diagram of the proposed system

When a light beam propagates through the FBG arrays of different grating periods, there will be a gradual shifting of Bragg wavelengths for various colors. The FBGs are inscribed in a single-mode fiber (SMF) to facilitate the single mode propagation. Now the pulse containing Bragg wavelength will be reflected back via circulators and afterwards it can be detected by optical spectrum analyzer (OSA) or any suitable photodiodes like avalanche photodiodes (APD) or PIN photodiodes. In general, photodiodes will translate the optical signal into an electric signal. Thus for each wavelength, there will be a specific current. These values of currents will be compared through a calibrated micro-controller unit which performs as a decision circuit. Now based on the actual value of current, the particular color can be detected. An LCD or LED display can be connected with the microprocessor unit to show the desired color as the output. In this detection system, the use of SMF offers certain advantages which include same core-diameter, same cladding-diameter, same core refractive index and same cladding refractive index for the variations in grating periods. There are also some other choices instead of using SMF. For example, low cost multi-mode fiber (MMF) may be a good option in this regard. But if it would be used in this system, there might be specific disadvantages in some aspects. Many modes of MMF would give rise to the occurrence of multiple Bragg wavelengths for a single color. Consequently, it would be difficult to distinguish among different colors and thus the MMF could lead to a faulty detection system.

IV. CONCLUSION

In this paper, we have presented a new way of detecting a particular color utilizing FBG as the specific wavelength selective device. To the best of our knowledge, a color sensor system based on FBG is designed for the first time. Though the experimental set up could not be performed due to some limitations, but we hope it will be possible to implement this method and such system will find its application in path finding robot, identifying things for the color-blind and blind people etc. Further analysis can be done for detecting more than 7 colors, even hundreds of colors. Moreover, it can be also possible to calculate the percentage of RGB in a particular color or in a mixture of color.

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