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Distributed Bragg reflector laser-based sensor for chemical detection

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Abstract

In this paper we present a novel sensor based on the modification of a distributed Bragg reflector (DBR) laser: the optical path length of a resonant cavity is changed thus changing the resonant frequency. The external cavity of the DBR laser, with a sensitive element within is used to detect chemical species and temperature. We will show the expected resolution as well as preliminary experimental results.

Keywords: DBR laser; Chemical sensor; Evanescent field

1. Introduction

Areas such as highly sophisticated fabrication processes and environmental monitoring have a growing demand for compact, low-cost, and real-time sensors. Of great interest is the detection of various liquids and gaseous species under harsh environmental conditions. Optical techniques provide attractive solutions to that demand. The advances in integrated optical components and fiber-optical devices over the past few years have opened a wide range of optics-based sensors. Many integrated optical sensors use the ability of the species in question to change the refractive index of a sensitive material placed within the penetration depth of an evanescent field [1,2]. In this work we present the novel approach of using this technique inside a resonant optical cavity to enhance the device sensitivity. The species in question are to change the index of refraction of the sensitive element thus changing the effective length of the cavity. The change of cavity length will result in a shift of the oscillation frequency of the laser, which is proportional to the concentration of the chemicals [3].

We use a semiconductor gain section with an external fiber cavity where the optical feedback is provided by a distributed Bragg reflector (DBR), which is written into the fiber forming the DBR laser. It is obvious that the resolution is strongly dependent on the resolvable frequency shift of the output of the DBR laser. The observable shift is limited by the line width and the stability of the DBR laser. To reduce the line width of the DBR laser, losses inside the cavity have to be minimized [4] and a stable packaging should be used. To filter the effects of temperature and strain and to minimize errors in the frequency shift measurement, a second DBR laser can be used as a reference to enable heterodyne detection. Here both lasers have to be designed such that environmental influences affect both lasers in the same way. The spatial separation of the lasers has to be small, for both lasers need to be exposed to the same environmental stress.

2. Experimental set-up

Fig. 1a shows a longitudinal cut of the single mode fiber (SMF) forming the external cavity of the DBR laser, containing the sensitive element used for the sensor. Here, L_t and L_s are the effective lengths of the total cavity and

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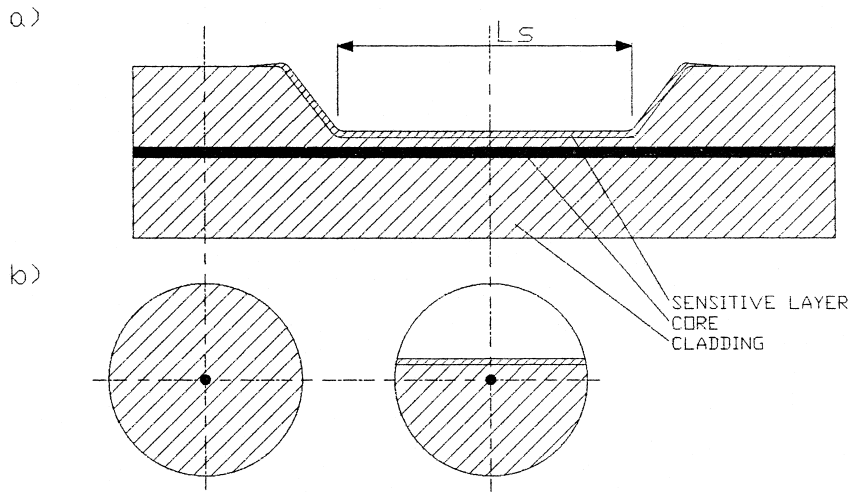

Fig. 1. Section of the cavity with the sensitive element: (a) longitudinal cut, (b) cross cut (unpolished fiber and after polishing and coating).

the sensitive section, respectively. A section of the cladding inside the cavity is removed, creating the D-shaped fiber shown in Fig. 1b. Leaving only a thin layer of cladding on one side of the core and adding a sensitive layer on top; the evanescent field is allowed to penetrate into the sensitive film. A change of the refractive index of the sensitive layer will change the effective length of the cavity thus shifting the resonance frequency.

Fig. 2 shows the proposed experimental set-up for the DBR laser-based chemical sensor. The top figure presents the currently used sensor. The output of an InGaAsP/InP MQW laser is butt-coupled to a SMF containing the sensitive element and the DBR. The front facet of the laser and the adjacent fiber facet are AR-coated to a reflectivity lower than 10^{-3}. The back facet of the laser is cleaved providing a 32% reflectivity. Using a directional coupler

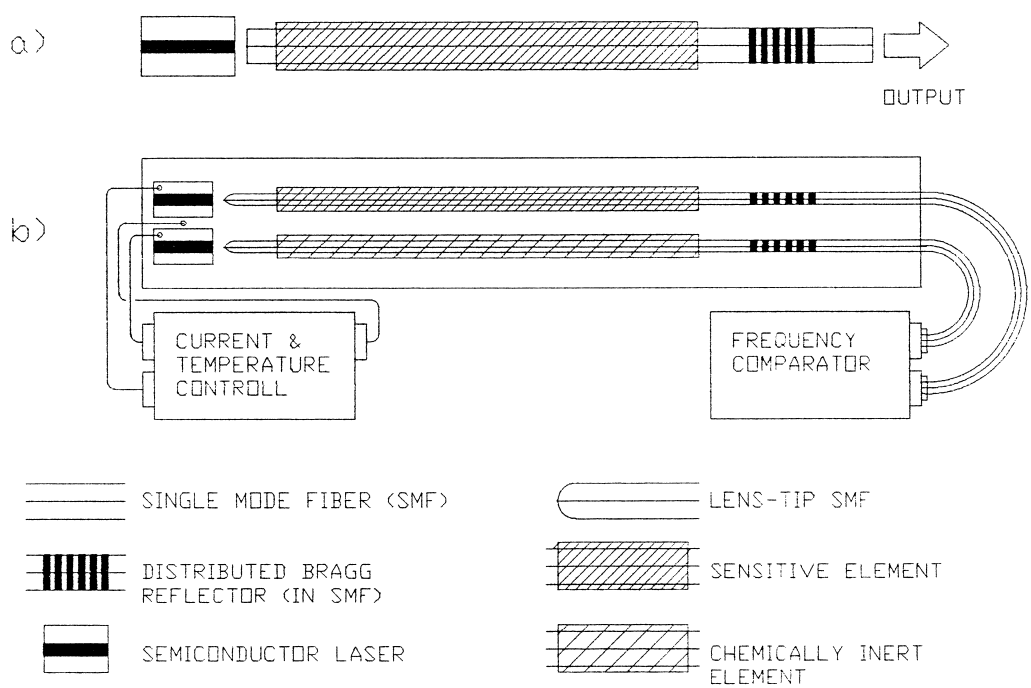

Fig. 2. (a) Single line sensor. (b) Two-line set-up using heterodyne detection.

the output from the DBR laser is fed to an optical spectrum analyzer (OSA) and a scanning Fabry–Perot interferometer (FPI) to monitor the output. The entire coupling device is temperature controlled.

The bottom figure shows a more advanced set-up. In this two-line approach a second identical arm is used as a reference to take temperature, strain and other environmental fluctuations into account. Since only one arm is exposed to the species in question, the frequency between the two lasers is changed. Other influences on the lasers will affect both lasers in the same way, thus not changing the frequency separation. A high speed detector and a RF spectrum analyzer measure the frequency difference. The two-line set-up will enhance sensitivity greatly since the resolution will no longer be limited by the stability of one laser, but by the relative stability of the two. To decrease the line width, the coupling efficiency is improved by using lens-tipped fibers.

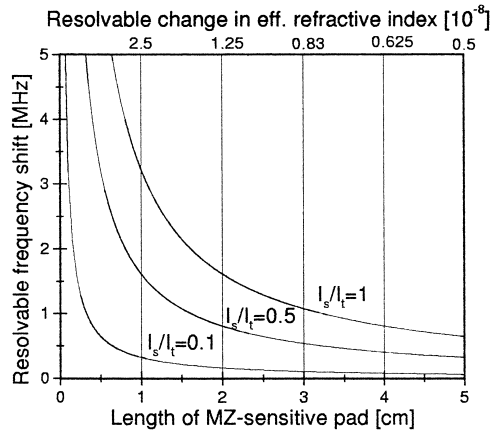

Fig. 3. For certain ratios of l_s/l_t the expected resolution is plotted. The resolvable change in effective refractive index is compared to a Mach–Zehnder-based sensor of varying length. Here we assumed a resolvable phase shift of 1×10^{-3} rad.

3. Resolution

Sensing is based on a shift of the resonance frequency by either changing the reflectivity peak of the DBR or by altering the effective cavity length in the presence of the chemical.

In the case of chemical detection, the length of the sensitive section is $L_s = N_s l_s$, where N_s is the effective refractive index of the sensing section and l_s is the physical length of the sensitive element as indicated in Fig. 2. Since l_t is the physical length of the total resonator, the fraction of l_s/l_t is always smaller than 1. Keeping the same lasing mode, the shift in resonance frequency caused by a change in effective length ΔL can be calculated as

$$\Delta\nu = -\nu\left(\frac{\Delta L}{L_t + \Delta L}\right). \tag{1}$$

Here L_t is the optical path length of the total resonator (with the sensitive element being a fraction thereof), $\Delta\nu$ is the resulting shift in resonance frequency, ν is the lasing frequency, and ΔL is the change in optical length due to a change ΔN in N_s. Using $\Delta L = \Delta N l_s$ we can get from Eq. (1)

$$\Delta N = -\frac{\Delta\nu}{\nu + \Delta\nu} N_t \frac{l_t}{l_s}, \tag{2}$$

where ΔN can also be considered the minimum resolvable change in effective refractive index if $\Delta\nu$ is the smallest resolvable frequency shift.

For three different ratios of l_s/l_t the resolvable shift in resonance frequency as a function of a change in N_s is shown in Fig. 3. The resolvable shift in effective refractive index is compared with a Mach–Zehnder-based sensor, where we assumed a resolvable phase-shift of $\delta = 10^{-3}$ rad [5]. Here we get for the resolvable change effective index ΔN from Ref. [6]

$$\Delta N = \frac{\delta\lambda}{2\pi l}, \tag{3}$$

where $\lambda = 1.55$ μm and l is the length of the sensitive pad. The assumed Mach–Zehnder-based sensor can resolve changes in the effective refractive index of 1.25×10^{-8} inside the sensitive pad of 2 cm length. A DBR laser-based sensor can resolve the same change if half the cavity is covered with a sensitive film and a frequency shift of 1 MHz is resolvable.

In the single line approach the measurable shift in frequency is directly related to the line width of the DBR laser and the stability thereof. In the case of the two-line set-up, the measurable shift is equal to the line width of the two DBR lasers and their relative stability. Using comparable DBR laser designs line widths well below the MHz-regime [7] and down to less than 100 kHz [8,9] have been measured. Reported temporal instabilities of the center wavelength in the order of several hundred MHz are assumed to be due to environmental fluctuations like temperature and strain. The usage of the two-line set-up is supposed to eliminate those instabilities because the lasers will correspond in the same manner. Due to the fact that the resolution of the DBR laser-based sensor is independent of the actual length of the sensitive element, instabilities due to large spatial extensions, common for the Mach–Zehnder-based devices, can be avoided, since only the fraction of l_s/l_t limits the resolution. The response time is limited by the sensitive element: as soon as the sensitive section changes its index of refraction a shift in resonance frequency will occur.

4. Experimental results

4.1. Chemical detection

As a first step the DBR laser, formed by the semiconductor laser, the SMF, and the DBR, is tested. At this stage we have only used one laser, which output we have monitored with an OSA and a scanning FPI. The set-up, used for all the measurements presented, is shown in Fig. 2a. Here the output of a semiconductor laser is butt-coupled into a SMF, where the DBR (grating) is written within. The output of the DBR laser is split up by a 3-dB coupler and fed to the OSA and FPI. The spectrum is shown in Fig. 4. Here the line width is limited by the OSA used, but was measured with the FPI to about 20 MHz, which included temporal instabilities of the laser and of the FPI.

To demonstrate the feasibility of the chemical sensor, a thin polymer film sensitive to acetone and toluene vapor has been used for the sensitive element, which was then placed into an enclosure where the vapor could be added. The operation of the DBR laser is monitored with the FPI before adding the vapor and while being surrounded by it. At this stage acetone vapor of unknown concentration was used. Fig. 5 shows the result of that measurement: the figure shows a total of four spectra of the DBR laser in multi-mode (longitudinal) operation; two without acetone vapor (solid line) and two with acetone vapor (dashed line). We have included two measurements of each state to show the magnitude of the instability of the laser in comparison to the shift resulting from the addition of acetone vapor. The modes were down-shifted by about 130 MHz and returned to the original position after the vapor has gone, within experimental errors. The response time is limited by the sensitive layer and was observed to be below 1 s. Thus we have demonstrated the feasibility of a chemical sensor based on the spectral shift. To fully exploit the sensitivity capabilities of the device undergoing efforts are being developed to improve the laser stability and to implement heterodyne detection with a reference laser for frequency comparison [3,10].

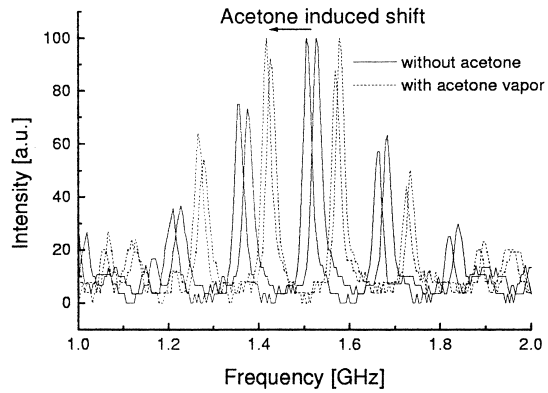

Fig. 5. The presence of acetone vapor induces a shift in the output frequency of the DBR laser. This figure shows four snapshots of the spectrum, two with and two without acetone vapor.

4.2. Temperature detection

The expected response to temperature effects of the DBR is given by Ref. [11] as

$$\frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial T} = 6.67 \times 10^{-6}\ \mathrm{K}^{-1}. \tag{4}$$

Here T is the temperature and λ_B is the wavelength of the reflectivity peak of the Bragg grating.

The temperature of the surrounding changes the reflectivity peak of the grating thus shifting the frequency of the laser. To test the effect of temperature on the output of the DBR laser, the grating was placed into a temperature controllable environment (not the entire laser, since the temperature of the gain medium has to be controlled separately). Fig. 6 displays the measurement. Here the experiment verifies the expected response given by Eq. (4) within experimental errors.

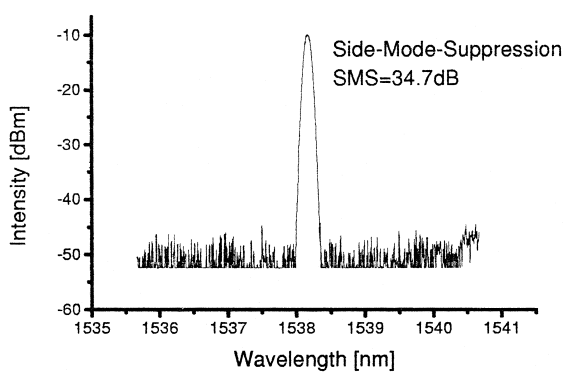

Fig. 4. Spectrum of the DBR laser with a side mode suppression of 34.7 dB.

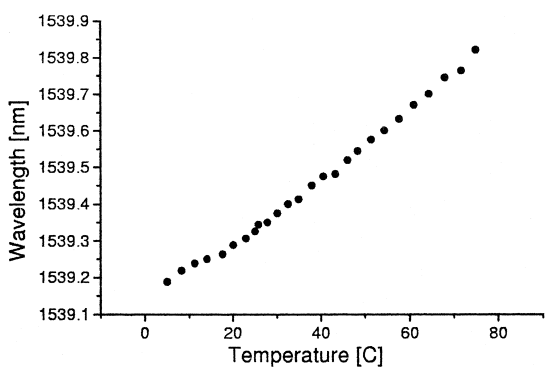

Fig. 6. Oscillation frequency of the DBR laser for varying temperature.

5. Discussion and conclusion

A DBR laser has been used to realize a sensor based on the modification of an optical resonator. The ability to sense the presence of acetone vapor and to measure temperature has been shown for the single-channel approach (without reference source). The strong effect of temperature on the spectrum of the DBR laser demands the two-line set-up for high resolution chemical measurements, since a second source can be used to filter the effects of temperature. The same behavior is expected for strain and humidity. Thus fluctuations of the DBR laser, which are based on these and similar factors can be eliminated using a reference source and heterodyne detection, promising a significantly higher resolution. Not only the design of a chemical sensor insensitive to environmental fluctuations is possible but also the design of a multi-functional array, measuring several chemicals and environmental changes at the same time. The simplicity of the approach and the cost of the components enable applications, which require many different sensor heads and harsh environmental conditions are present.

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References

[1] W. Lukosz, Sensors Actuators B 29 (1995) 37.
[2] O. Parriaux, G.J. Veldhuis, J. Lightwave Technol. 16 (4) (1998) 573.
[3] S. Ten, M. Fallahi, N. Peyhambarian, SPIE Proc. 2763 (1996) 64.
[4] T. Kunii, Y. Matsui, Opt. and Quantum Electron. 24 (7) (1992) 719.
[5] H. Helmers et al., Appl. Optics 35 (1996) 676.
[6] M. Born, E. Wolf, Principles of Optics, 6th edn., Pergamon, New York, 1993.
[7] P.A. Morton et al., Appl. Phys. Lett. 64 (20) (1994) 2634.
[8] J.J. Pan et al., Fiber grating stabilized laser source for dense WDM systems, OFC 1997 Technical Digest, 1997, pp. 213–214.
[9] D.M. Bird, Electron. Lett. 27 (13) (1991) 1115.
[10] S. Mendes et al., New optical detection techniques for chemical sensors, SPIE Proceedings, Photonics West, 1998, to be published.
[11] A.D. Kersey et al., J. Lightwave Technol. 15 (8) (1997) 1442.