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Novel chemical sensor/biosensor platform based on optical multimode interference (MMI) couplers

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Abstract

We present a novel platform for chemical sensing and biosensing. The working principle is based on the interference properties of an optical multimode interference coupler. A humidity sensor has been implemented as a proof of principle. It has been realised using hybrid sol–gel planar technology to allow integration on a silicon substrate.

Firstly, we describe the theory of multimode interference and we model the sensor response to the change of the sensing layer refractive index. Then, the sensing material is described and characterised regarding optical and sensing properties. Finally, the prototype device is characterised. A linear response to relative humidity is obtained and it is shown that sensitivity can be tuned using the MMI design technique.

Keywords: Chemical sensor; Biosensor; Optical couplers; Multimode interference (MMI); Hybrid sol–gel

1. Introduction

The development of optical sensors and fibre-optic sensors has been revolutionised over the last two decades with the improvement of optical device fabrication [1,2] and the proliferation of sensing applications [3,4].

Intrinsic optical fibre sensors operate on the principle that guided light is perturbed by external parameters, e.g. mechanical stress, temperature, etc. One of the main methods to access, and thus modify, the light propagating inside the fibre is to remove the protective coating and polish down the cladding region of the fibre [5]. The evanescent part of the electromagnetic wave then travels in the medium to be measured. Intensity and phase perturbation measurements can be correlated with properties of the medium. In order to achieve a specific sensor response a replacement cladding material is often coated or immobilised on the structure whereby the coating refractive index (or other optical property) is sensitive to a certain physical/chemical/biological property.

In order to compete with other existing devices, key parameters such as cost, size, sensitivity, sensing range, flexibility, ease of use and integration have to be optimised. Moreover, in terms of mass production, planar technologies are much more attractive for sensors than those based on optical fibres. Using sol–gel processed hybrid materials, we have developed planar lightwave circuits for use in telecommunications [6]. This technology is also strongly suitable for sensing applications due to the versatility of the process and the tuneability of the material.

We present here a new generic platform for refractometric sensing using an integrated optical sensor. It is based on multimode interference couplers, which are easy to fabricate, and which can be adapted to different applications by simply modifying their width and length. The multimode section (rectangular area in Fig. 1) can be covered with an appropriate sensing material that suits the particular application.

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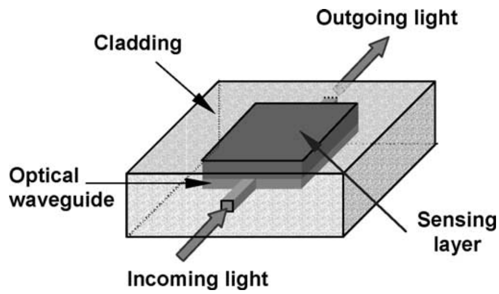

Fig. 1. Platform principle.

As a proof of principle, we have developed a humidity sensor. Firstly, we describe the theory of light propagation in a MMI coupler. Then, the development and characterisation of a humidity sensitive material is detailed. Finally, the experimental results of the sensing devices are presented and these clearly illustrate the feasibility of sensors based on this new platform.

2. Optical modelling

MMI couplers are generally composed of single-mode input and output waveguides coupled to a central multimode waveguide (see Fig. 2).

The singlemode incoming light $\psi(x)$ from an input waveguide is coupled onto the different modes $\psi_v(x)$ of the multimode section, where v is the mode order and c_v are the excitation coefficients [7].

$$\psi(x) = \sum_{v} c_v \psi_v(x) \tag{1}$$

In the central section, the different modes propagate individually at different speeds, which depend upon a number of parameters including the refractive index of the layer covering the multimode section, in our case the sensing layer. Those different speeds induce a phase shifting of the modes along the propagation path. This affects the resulting electromagnetic field intensity profile due to constructive and destructive interference.

When all the modes have experienced a 2π phase change, the intensity profile of the input field is imaged. This occurs after a certain propagation distance $d = 3L_\pi/4$, where L_π is

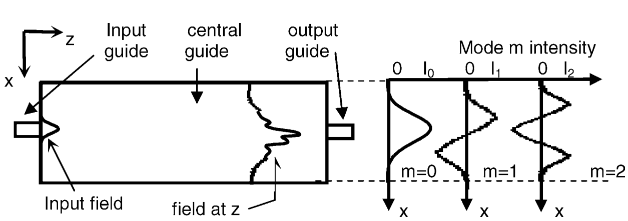

Fig. 2. Top-view MMI coupler layout (left) and some of the central waveguide modes profiles(right).

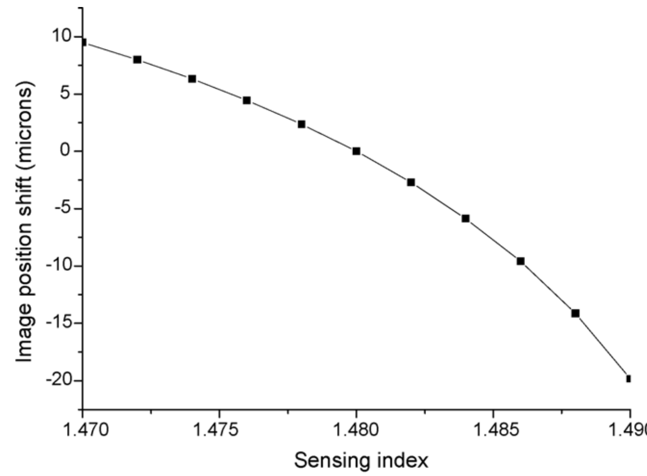

Fig. 3. Image position shift with sensing index.

the beat length:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_i} \tag{2}$$

with β_i the propagation speed of mode i.

The effective indices of fundamental and first order modes depend on the sensing layer index. A calculation, based on effective index simulation, of the image shift dependence versus sensing layer index has been computed and is shown in Fig. 3.

The shift of the image relative to its initial position can be related to the power coupled to the output waveguide. The output evanescent field profile $\Psi(x,d)$, resulting from the interference between the modes after a propagation distance d is overlapped with the single-mode profile of the output waveguide to compute the optical power transmission T:

$$T = \left(\frac{\int \Psi(x, d)\psi(x)\,\mathrm{d}x}{\sqrt{\int \psi^2(x)\,\mathrm{d}x}} \right)^2 \tag{3}$$

This enables the calculation of the response of the sensor to a sensing layer index change. We assume $\psi(x)$ the single-mode output waveguide field profile is gaussian (fitted radius is 3.335 μm). The input field profile to the MMI section is identical to the single-mode output profile and propagates in free space and this also applies to the self-image. From free space gaussian beam propagation theory, the relationship between transmission and self-image position can be computed. Using Fig. 3 we can then express transmission versus sensing index. Using the Finite Difference Beam Propagation Method (FD–BPM), this transfer function has been computed as shown in Fig. 4. The following parameters were employed in the model: each layer is 6 μm thick; the single-mode waveguide is 6 μm wide and the multi-mode waveguide is 50 μm wide; the cladding index is 1.49 and the core index is 1.5; the vacuum wavelength is 1310 nm.

The sensing device is based on a symmetric three-layer system (see Fig. 5): a buffer layer (BL) to isolate light from