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# Temperature characterization of evanescent field coupling between a single-mode fiber and a multi-mode waveguide overlay

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ABSTRACT. A single-mode fiber at 1.06 $\mu$m was side-polished on a silica substrate in order to remove its cladding and expose the evanescent field; by depositing on it a thin layer of Cargille refractive index oil of uniform thickness (nominally 20 to 80 $\mu$m), a multi-mode waveguide overlay was formed. Power coupling efficiency between these two waveguides as a function of temperature was characterized in detail with several refractive index oils, using a Nd-doped fiber laser source which had a spectral bandwidth of 6.0 nm; up to 91% modulation of the coupling efficiency was observed with this source. This technique has been applied to accurately measure the thermo-optic coefficient of the refractive index oil, obtaining $\partial n/\partial T = (-4.23 \pm 0.4) \times 10^{-4}$.

RESUMEN. Una fibra unimodal de 1.06 $\mu$m fué pulida lateralmente sobre un substrato de silicio para remover su recubrimiento y exponer el campo evanescente; depositandole una capa delgada de aceite de índice de refraccion Cargille con espesor uniforme (nominalmente de 20 a 80 $\mu$m), se formó una sobrecapa de guía de onda multimodal. Se caracterizó en detalle la eficiencia de la potencia de acoplamiento entre las dos guías de onda como función de la temperatura con aceites de varios indices refractivos, usando una fuente de fibra láser dopada con Nd, la cual tiene un ancho de banda espectral de 6.0 nm. Con esta fuente se observó arriba del 91% de modulación de las eficiencias de acoplamiento. Esta técnica se ha aplicado a medidas de precisión del coeficiente termo-óptico del aceite de índice de refracción, obteniendose $\partial n/\partial T = -(4.23 \pm 0.4) \times 10^{-4}$.

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## 1. INTRODUCTION

During the last few years there has been increasing interest in fiber optical components performing functions such as modulation, switching, filtering and signal multiplexing. Recently an in-line fiber optic modulator operating at a wavelength of 1.3 $\mu$m with a source spectral width of less than 2.0 nm has been developed [1, 2]. This is based in the evanescent field coupling technique between a single-mode fiber, with removed cladding, and a non-linear planar multi-mode wave-guide overlay with high refractive index and

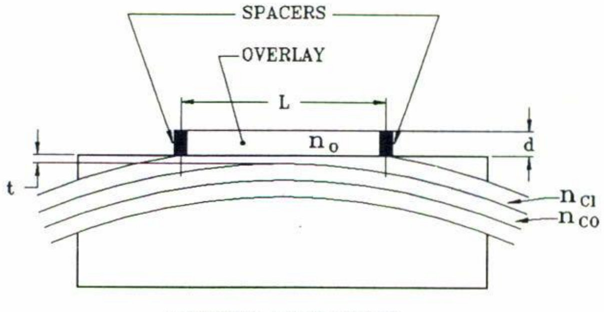


FIGURE 1. Schematic diagram of the an in-line fiber optic modulator.

high electro-optical coefficient. Modulation is obtained by applying a voltage between two electrodes, deposited previously on both surfaces of the overlay and in optical contact with the single-mode fiber. Through the electro-optical effect, the effective index of the planar wave-guide highest mode may be made to match the effective index of the fiber; when this happens the signal through the fiber is coupled into the planar wave-guide. This new device enables the signal to be modulated within the fiber avoiding breaking it for insertion of a bulk modulator. In principle, it has the potential to overcome the problems presented by the integrated optics technology and can be applied in optical communications, cable TV distribution, optical sensing, laser printing, laser Q-switching and mode-locking.

In the present work we describe our first experimental results towards the making of an in-line fiber optic modulator operating at a wavelength of 1.06 $\mu$m using a Nd-doped fiber laser with spectral bandwidth of 6.0 nm. We are concerned with two main issues: a) temperature characterization of the fiber-overlay power coupling efficiency; b) determination of whether a useful depth of modulation of the coupling efficiency can be achieved with the fiber laser source, given its relative large bandwidth. The latter point is of particular importance in some applications involving fiber laser printers, in which a depth of modulation of at least 10:1 (90%) is required.

This work is divided in two parts. The first part is a theoretical review of the problem in which the physical parameters and their influence on power coupling efficiency are determined. The second part describes in detail the characterization of the fiber-overlay coupling efficiency using several refractive index oils through variation of temperature in the range 25°C to 50°C. This technique is applied to determine the thermo-optic coefficient of the refractive index oil; it will be shown that the thermo-optic coefficient can be determined with 12% accuracy. It will also be shown that 91% depth of modulation can be achieved with $2.470 \times 10^{-4}$ index variation.

## 2. FIBER-OVERLAY COUPLING SYSTEM

The system is based on the evanescent field coupling technique and consists of a single-mode optical fiber with an exposed core-edge in optical contact with a multi-mode planar

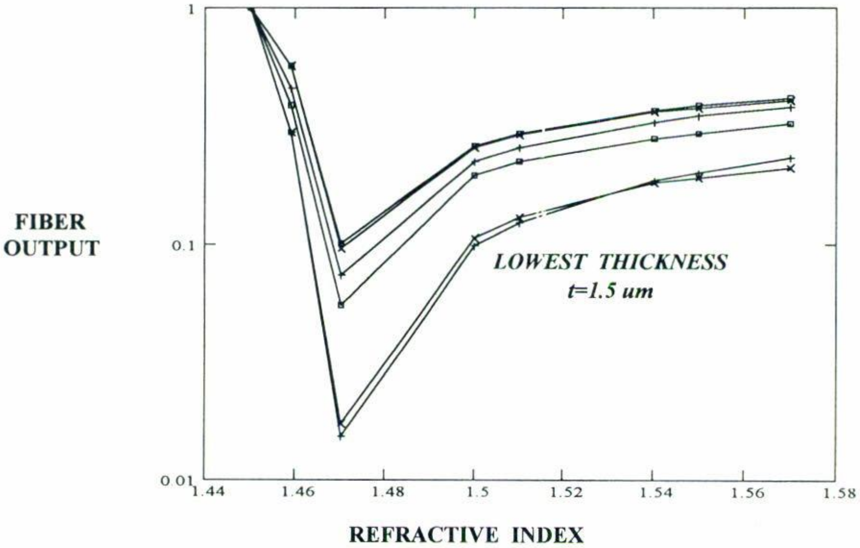


FIGURE 2. Fiber throughput for six fused silica blocks; estimated remaining cladding thickness $t = 1.5\ \mu$m for bottom graph and $t$ increasing from bottom to top. The effective interaction length is 5.0 mm. For a given refractive index we can see the effect of the remaining cladding, and for a given block we can see the coupling strength when the refractive index changes.

wave-guide. The signal travelling through the fiber is coupled into the multi-mode wave-guide that disturbs the evanescent field in the fiber core-edge region. Figure 1 shows the structure of the fiber optic-overlay coupling system. The spacers determine the thickness of the overlay.

There are two ways of reaching the core-edge. The first is by preform grinding and drawing a D-shaped fiber [3], in which case it is possible to obtain a very large number of devices from one preform and a long effective interaction length. The second method, which was used here, is to remove the cladding by polishing [4]. In this case the single-mode fiber at a wavelength of 1.06 $\mu$m is bonded to a fused silica block with a curved slot having a radius of curvature ($R$) that determines the effective interaction length ($L$). Then the top surface is polished and the desired remaining cladding $t$ is obtained. (See Fig. 1).

The thickness ($t$) determines the coupling strength and together with the effective length ($L$) determines the out-coupled power for a particular overlay. This means, that if we put the exposed core-edge in optical contact with a material having a refractive index ($n_0$) close to that of the cladding index, the out-coupled power decreases when the thickness ($t$) increases and when the interaction length decreases. In addition, the largest out-coupled power occurs when ($n_0$) is very close to the cladding index or the effective refractive index of the fiber. We measured these effects, and typical results are shown in Fig. 2 for six fused silica blocks having different remaining cladding thickness $t$, which can be estimated according to [5]. Notice that if ($t$) is too small, the system will exhibit a large insertion loss. One of these blocks with a remaining cladding $t = 1.5\,\mu$m (bottom graph) and effective length $L = 5.0\,\mu$m was used in the experiments described below.

The overlay is any kind of optical material that forms a planar multi-mode wave-guide with an effective refractive index $n_{e0}$ smaller than the overlay refractive index $n_0$ and greater than the fiber cladding refractive index $n_c$ ($n_c < n_{e0} < n_0$). When this condition is satisfied guidance may occur in the overlay, and efficient directional coupling with low transmission occurs only when the effective refractive index of the overlay matches the effective refractive index of the fiber ($n_{ef} = n_{e0}$). This condition will be more easily satisfied by the overlay highest order modes. The approximate eigenvalue equation for the mth-order mode at a wavelength $\lambda$, propagating in a symmetric wave-guide of thickness $d$ is given by [6]

$$2\left(n_0^2 - n_{e0}^2\right)^{\frac{1}{2}} d = m\lambda, \tag{1}$$

where $n_{e0} = n_{ef}$ for efficient coupling. We can see that, to this approximation, the coupling is not polarization dependent and the condition for matching can be obtained by changing either the refractive index of the overlay or the wavelength or the overlay thickness. Then, when any of these parameters is changed, the effective refractive index of the overlay changes and matches the effective refractive index of the fiber mode Then one may expect to observe a periodic transmission intensity function that corresponds to each mode being tuned in and out of resonance with the fiber mode. Notice that there are no special requirements imposed on the overlay refractive index, making it possible to use a wide range of optical materials.

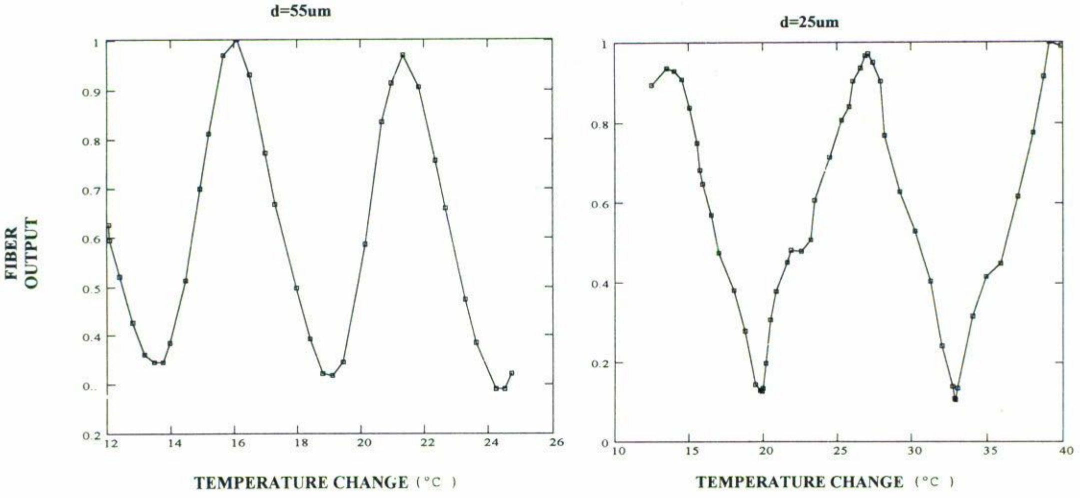
## 3. EXPERIMENTAL RESULTS

A thin film of Cargille refractive index oil with $n_0 = 1.510 \pm 0.0002$ at 25°K and wavelength 1.06 $\mu$m, and thermal coefficent $\partial n/\partial T = -3.8 \times 10^{-4}$ C$^{-1}$ was used as overlay. Using an aluminium spacer to control the desired overlay thickness $d$ and a hot plate to change the oil temperature (hence the index), intensity modulation with changing temperature was readily observed. The results are shown in Fig. 3 for two different overlay thicknesses $d$.

Using Eq. (1) it is easy to show that the change in $d$, $\lambda$ or $n_0$ required to achieve phase matching between two consecutive planar wave-guide overlay modes and the fiber mode is

$$1 = \frac{2dn_0}{\lambda\left(n_0^2 - n_{ef}^2\right)^{\frac{1}{2}}}\,\delta n_0 + \frac{2\left(n_0^2 - n_{ef}^2\right)^{\frac{1}{2}}}{\lambda}\,\delta d - \frac{2d\left(n_0^2 - n_{ef}^2\right)^{\frac{1}{2}}}{\lambda 2}\,\delta\lambda. \tag{2}$$

For these experiments we can assume that the overlay thickness and the wavelength are fixed. The first assumption is based on the fact that the thermal expansion of the spacers and the overlay oil is too small for the temperature change used in this work ($\ll 1\,\mu$m). Then, Eq. (2) is reduced to only the first term on the right hand side; it shows that, for a given wavelength $\lambda$ and overlay thickness $d$ a relatively large $\delta n_0$ is



(a) (b)

FIGURE 3. Graph that shows coupling power between a single-mode fiber and a planar multimode waveguide overlay for two particular overlay thicknesses. We can see that the modulation shape is deformed for smaller $d$. The temperature change required to couple two consecutive planar waveguide overlay modes is 5.4°C. a) $d = 55\,\mu$m, b) $d = 25\,\mu$m. On-off modulation ratio of 89% is obtained with this thickness.

required to achieve phase matching between successive overlay modes. From Eq. (2), one estimates $\delta n_0 = \lambda\sqrt{n_0^2 - n_{ef}^2}/(2dn_0)$, with $\lambda = 1.06\,\mu$m, $n_0 = 1.510$, $n_{ef} = 1.467$ (taken from Fig. 2) obtaining $\delta n_0 = 0.0022$ for $d = 55 \pm 5\,\mu$m. Furthermore, Fig. 3 shows that $\Delta T = 5.4$°C so that the thermo-optic coefficient is $\delta n/\delta T = -4.23 \times 10^{-4}$ C$^{-1}$ which is within 12% of the nominal value.

To achieve phase matching, (and coupling) between two successive overlay modes, it is necesary to modulate the effective index of the overlay wave-guide. Then from Eq. (1) it is possible to find expressions that relate the refractive index change and wavelength change with thickness change, namely,

$$\delta n_0 = \frac{2dn_0}{n_0^2 - n_{ef}^2}\,\delta d, \tag{3}$$

$$\delta\lambda = -\frac{2d}{\lambda}\,\delta d. \tag{4}$$

From these expressions, it is possible to relate refractive index change with wavelength change by

$$\delta\lambda = -\frac{\lambda}{n_0\left[1 - n_{ef}^2/n_0^2\right]}\,\delta n_0. \tag{5}$$

This last equation is not an explicit function of $d$ and allows us to calculate the resonance spacing or free spectral range (FSR) by measuring the index change between two

TABLE I. Characteristics of the modulation obtained using Cargille refractive index oil $n_0 = 1.510 \pm 0.0002$ and $\partial n/\partial T = -4.23 \times 10^{-4}$ K−1 ($\partial n/\partial T = -3.80 \times 10^{-4}$ C−1 nominal value). The first two parameters are measured directly from the graph and the last three are calculated using Eqs. (2) and (5).

| $\delta n_{\mathrm{max-min}}$ $\times 10^{-3}$ | depth of modulation % | $d$ ($\mu$m) overlay | FSR nm | FWHM (nm) resonance | FSR/FWHM= 2 |
|---|---|---|---|---|---|
| 1.147 | 67.00 | 55 | 25.65 | 13.50 | 1.90 |
| 2.104 | 71.00 | 30 | 52.17 | 25.00 | 2.08 |
| 2.254 | 83.60 | 27 | 59.07 | 27.51 | 2.14 |
| 2.318 | 89.00 | 25 | 61.76 | 32.51 | 1.90 |
| 2.470 | 91.00 | 20 | 80.77 | 37.51 | 2.15 |

successive resonance modes; and measuring the index change at half of the resonance mode we can calculate the bandwidth (FWHM). Moreover, it shows that the bandwidth of the resonance mode decreases with increasing overlay index and decreasing $d$. Thus, measuring the index change and using Eqs. (2) and (5) we calculated the overlay thickness, the free spectral range and the bandwidth of the resonance mode. As one would expect with a two-mode interferometric device, the scaling FSR/FWHM must remain equal to two, as indeed was the case here (within an experimental error of ±7.5%).

We also measured the coupling efficiency or depth of modulation and the index change between the maximum and minimum of the resonance. This is an important parameter because it gives the index change required to obtain a given depth of modulation that, in turn, allows to estimate the required voltage if an electro-optical wave-guide is to be used. All these results are shown in Table I.

There are three important parameters for the performance of the couplin g process. A large depth of modulation, a narrow bandwidth and small index change between the maximum and minimum of the resonance. From Table I we can see that there is an inverse relationship between the first and second parameters. This means that best depth modulation (and a broad bandwidth) occurs with the smallest $d$. The reason for this is clear: as $d$ increases the number of overlay wave-guide modes increases and get spectrally closer (the FSR decreases). If the finite bandwidth of the so urce is comparable in magnitude with the FSR, it becomes increasingly difficult to descriminate the in and out-of resonance conditions, resulting in a poor depth of modulation.

## 4. CONCLUSIONS

We have shown that using the evanescent field coupling technique it is possible to calculate the thermo-optic coefficient of a thin overlay within 12% accuracy. This gives the possibility of measuring small changes of the refractive index of the overlay and making a temperature sensor. Moreover, it has been shown that it is possible to get a modulation of the coupling efficiency of up to 91% for the 1.06 $\mu$m output of a Nd-doped fiber laser which had a spectral bandwidth of 6.0 nm. The main characteristics of the device and the behavior of its different parameters were established. According to the results shown in Table I, it is not possible to get a narrow bandwidth and a large coupling efficiency at the same time; but it is possible to decrease $\delta n_{\max-\min}$ and the FSR by increasing $d$.

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