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Selective coupling of fibre modes using surface-guided Bloch modes supported by dielectric multilayer stacks

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Abstract

The surface-guided Bloch modes guided by the interface between a multilayer dielectric stack and an external medium are highly dispersive. This makes attractive their use in mode-selective coupling of light into and out of side-polished multimode fibres. The particular case of a dual-mode fibre is modelled in this paper. Mode selection via surface-guided Bloch modes is found to offer advantages in comparison to selection via a single mode waveguiding film of the same average refractive index as the stack. Good modal selectivity is achievable together with high tunability, i.e., high sensitivity to the refractive index of the intervening layer between stack and side-polished fibre.

1. Introduction

Mode-selective coupling, i.e., the coupling of light into and out of individual modes of a multimode fibre. is a subject of continuing interest [1]-[3]. Mode-selective fibre couplers (MSFC's) are key components in short distance data transmission systems based on mode-division multiplexing [4] and have important applications in optical sensors based on few-mode fibres [5]. The MSFC concept is simple (see Fig. 1). A second waveguiding structure is brought in close contact with a side-polished section of fibre, a layer of material (e.g., oil) with an alterable refractive index in between. Exchange of power from a particular fibre mode to the second waveguide occurs via the evanescent fields, phase matching being attained by tuning the index of the intervening layer. Desirable device characteristics include low insertion loss, good tunability (i.e., high sensitivity to the index of the intervening layer) and very low cross-talk from the un-selected fibre mode.

A number of different types of MSFC have been reported. They show that whereas selection of the higher order mode may be achieved with high levels of selectivity against the fundamental mode [1] − [3], tuning to the fundamental mode suffers considerable cross-talk from the higher order mode. This has been demonstrated experimentally for a device based on evanescent coupling of fibre modes to a long-range surface plasmon mode [3]; the values obtained for the cross-talk are ~ -19.9 dB and ~ -1.8 dB when tuned to the LP_{11} and LP_{01} modes respectively. The cause is the deeper penetration of the modal field into the fibre cladding as the mode order increases, leading to much stronger coupling. As a result, even when the fundamental mode is correctly tuned in, there is unacceptably high cross-talk from the non-phase-matched higher order mode. In addition, unavoidable ohmic losses in the metal layer result in a broadening of the resonances. The consequence is a trade-off between loss and selectivity, severely limiting the overall device performance.

In this paper we show that the modal selectivity can be improved significantly by replacing the thin metal layer with a suitably designed AlGaAs multilayer stack. In addition, substantial improvements in tunability are made possible via the increased sensitivity of the modal phase-matching condition to the refractive index of the layer between the stack and the side-polished fibre. To provide a measure of the performance achievable with MSFC's based on SGBM's, an alternative MSFC design using a conventional planar dielectric waveguide instead of a multilayer stack is considered.

2. Surface-guided Bloch modes

Under the correct conditions, SGBM's appear at the interface between a low index medium and a multilayer dielectric stack [6]. A number of special features sets them apart from normal waveguide modes and makes them interesting for a whole range of applications [7], [8]. They are confined by total internal reflection and Bragg reflection, and their propagation constant lies within the stop-band of the stack, which can cover a wide range of effective indices if the index contrast of the stack is high. Their effective index is very sensitive to the index of the external medium, and since only one mode appears per stop-band, a substantial range of effective single-mode operation is achievable. As it is the Bragg condition which determines the approximate effective index of the SGBM, phase matching to a low-index fibre mode can be achieved despite the possibly high average index of the stack. This means that the optoelectronic functionality of the high index III-V system can potentially be combined with low-index glass fibre optics. Finally, they can exist for both TE and TM-polarizations and are virtually lossless provided the materials of the stack are nonabsorbing.

3. Waveguide modes

For comparison with the SGBM device, we choose a film of index equal to the average index of the stack, deposited on a silica substrate. In general, the highest order waveguide mode (WGM) supported by such a film shows the greatest sensitivity to the refractive index of the external medium. For a fixed film index, this sensitivity can be enhanced by reducing the film thickness, reducing at the same time the overall number of guided modes which are supported. The limiting case is a single-mode waveguide designed to phase-match to the fibre modes at a similar intervening layer index as in the case of the SGBM. Being highly sensitive to the refractive index of the surrounding medium, this WGM will mimic some of the properties of a SGBM.

4. Theoretical Model

The MSFC considered in this paper follows the general pattern outlined in the introduction. The refractive index profile used in the modelling is shown in Fig.2a, where the fibre has been replaced by a two-moded planar dielectric waveguide designed to simulate the LP_{01} and LP_{11} fibre modes. A layer of index matching oil of thickness h_{oil} and with refractive index n_{oil} is placed between the two-mode guide and the stack. Since the effective index of the SGBM changes much more rapidly with n_{oil} than the indices of the two-mode guide, one or the other mode may be selected by altering the refractive index of the oil. The refractive index profile of a competing MSFC design, employing a high index single-mode planar film in place of the multilayer stack, is shown in Fig.2b. The modes of this film are referred to as waveguide modes (WGM's).

As a starting point, the exact normal modes of the MSFC's will be calculated. Taking advantage of the relationship between the normal-mode approach and coupled-mode theory [9], the performance of the MSFC's can then be straightforwardly assessed. Since only two modes (and not the full three supported by the structure) are taken into account in this comparison, an approximation is involved; however, in the case of weak coupling the approximation is good, and gives a clear picture of the coupler performance. The coupling is considered to be weak as long as the splitting between the normal modes at the anti-crossing points is considerably smaller than the difference in effective indices between the two fibre modes. Having calculated the normal modes of the coupler, the range of parameters for which this approximation is valid can be established without difficulty. Assuming weak coupling, the maximum power P_{max} coupled to the SGBM/WGM from a fibre mode carrying the power P_0 is given by the familiar expression [9]

$$\frac{P_{max}}{P_o} = \frac{\kappa^2}{\kappa^2 + \Delta^2} , \qquad (1)$$

where κ is the coupling coefficient and Δ equals half the difference between the propagation constants β of the individual coupled modes (*not* the normal modes), including the self-coupling terms κ_s and κ_f:

$$\Delta = \frac{1}{2}(\beta_s - \beta_f + \kappa_s - \kappa_f) . \qquad (2)$$

Here, the index s refers to the SGBM/WGM and f denotes the fibre mode. The propagation constants Γ of the normal modes are given by

$$\begin{aligned} \Gamma_I &= \gamma + \sqrt{\Delta^2 + \kappa^2} \, , \\ \Gamma_{II} &= \gamma - \sqrt{\Delta^2 + \kappa^2} \, , \end{aligned} \tag{3}$$

where

$$\gamma = \frac{1}{2}(\beta_s + \beta_f + \kappa_s + \kappa_f) \, . \tag{4}$$

For the relevant range of parameters, the presence of the stack (or waveguide) does not alter the effective index of the fibre modes noticeably, and hence the fibre self-coupling contribution can be ignored. Using $\kappa_f = 0$ in (3) and (4), the SGBM/WGM self-coupling term κ_s can be derived as a function of the involved normal and individual modes, leading to the following equation for the coupling coefficient κ:

$$\kappa^2 = (\Gamma_I + \Gamma_{II})\beta_f - \Gamma_I \Gamma_{II} - \beta_f^2 \, , \tag{5}$$

where Γ_I and Γ_{II} are the propagation constants of the normal modes which correspond to the two interacting guided modes and β_f is the propagation constant of that fibre mode from which power is coupled to the SGBM/WGM. Finally, substituting (2) and (5) into (1), the maximum coupled power is obtained as

$$\frac{P_{max}}{P_o} = 1 - \left(\frac{\Gamma_I + \Gamma_{II} - 2\beta_f}{\Gamma_I - \Gamma_{II}} \right)^2 . \tag{6}$$

Knowing Γ_I and Γ_{II}, the coupling length follows immediately as

$$L_c = \frac{\pi}{\Gamma_I - \Gamma_{II}} . \tag{7}$$

This is the propagation distance needed to couple the power P_{max} from the individual fibre mode to the SGBM/WGM.

The normal modes are calculated by using a standard translation matrix method [7]. In this formalism, the field vector in one layer of the stack can be expressed in terms of the field vector in the adjacent layer by operation with a 2x2 translation matrix. An evanescent decay is assumed for the field in the outer fibre cladding. Similarly, the envelope of the field decays exponentially into the stack in accordance with the fact that the SGBM is located within the stop-band. By operation with the translation matrix, the boundary conditions for the associated electromagnetic field at the interfaces between the individual layers are fulfilled, leading to the dispersion relation of the normal modes. The coupler employing a conventional planar waveguide can be treated in an analogous manner; by satisfying the boundary conditions at each layer interface, the dispersion relation of the normal modes is derived easily. The associated field of the normal modes is assumed to be exponentially decaying into the outer fibre cladding and into the waveguide cladding.

5. Analysis of Performance

For the numerical analysis, a multilayer stack consisting of alternating layers of $Al_{0.1}Ga_{0.9}As$ (thickness h_1 = 65.6nm, refractive index at 830nm n_1 = 3.58), AlAs (h_2 = 75.4nm, n_2 = 2.99) and a topmost layer of $Al_{0.1}Ga_{0.9}As$ (h_f = 7.3nm) is considered. These parameters ensure that the TE-polarized SGBM can be phase-matched to the fibre modes at a wavelength of 830nm. This is the wavelength the coupler is designed for and at which all further numerical calculations were carried out. The effective index of the corresponding TM-polarized SGBM at 830nm is significantly larger than 1.45, the value around which a typical silica fibre supports guided modes. Hence, only coupling to the TE-polarized SGBM is considered in the following. The absorption band edge of undoped $Al_{0.1}Ga_{0.9}Al$ at room temperature is λ_g = 803nm as determined by its direct band gap. For AlAs, the indirect band gap yields λ_g = 572nm subject to insignificant phonon energy contributions and hence, both semiconductor materials are essentially nonabsorbing at 830nm. The planar waveguide simulating the fibre has a core index of 1.458 and a cladding index of 1.453. One side of the cladding is polished to a remaining thickness of 1μm. With a core thickness of 5.5μm, two guided modes are supported at 830nm.

In Fig.3, the effective index $n_{eff} = \Gamma/k_0$ of the normal modes of the coupler are plotted as a function of the refractive index of the oil layer. Here k_0 denotes the wavevector in vacuum. Three normal modes are supported as a result of the interaction of the two fibre modes with the SGBM. Away from the two coupling regions, two normal modes are fibre-like and change very little with oil index. The third normal mode is highly sensitive to the oil index and behaves like a SGBM. In the vicinity of each coupling region hybrid normal modes form, with a mixture of SGBM and fibre mode characteristics.

In Fig.4, the normalized maximum power coupled from each fibre mode is plotted as a function of oil index, for both the multilayer stack (solid lines) and the high-index waveguide (dotted lines). The oil thickness $h_{oil} = 1.8\mu m$ was chosen to ensure weak coupling in both cases. For coupling between the LP_{11}-like fibre mode and the SGBM, no calculations were performed for $n_{oil} < \sim 1.4145$. This is because (see Fig.3) one of the normal modes becomes radiative, escaping into the fibre cladding, i.e., $\Gamma/k_o < n_{cl}$. From Fig.4 it is evident that, when tuned to the fundamental fibre mode, the cross-talk from the higher order mode is ~ -26dB (SGBM) and ~ -31dB (WGM). When tuned to the higher order fibre mode, the cross-talk from the fundamental mode is ~ -36dB (SGBM) and ~ -46dB (WGM). The cross-talk from the higher order mode when tuned to the fundamental was found to be always higher than the cross-talk from the fundamental when tuned to the higher order mode. This is due to the above mentioned fact that the coupling to the higher order mode is relatively strong even in the case of phase mismatch as a result of the larger field overlap. The corresponding figures for the waveguide case are better, however the cross-talk can always be improved by increasing the thickness of the oil layer, resulting in a decrease of coupling strength and a longer coupling length. This is demonstrated for the SGBM in Fig.5, where cross-talk and coupling length for both fibre modes are plotted as a function of oil thickness, showing that there is a clear trade-off between coupling length and cross-talk. Aiming for a similar coupling length as in the WGM case, a cross-talk of $< \sim -30$dB is predicted for the fundamental fibre mode, which is similar to the corresponding cross-talk figure in the WGM case. However, even a value of ~ -26dB is quite acceptable in many applications as it is lower than the intermodal coupling in a weakly multimode fibre over distances typical for short length communication networks [10]. These values compare favourably with the theoretical predictions for an optimised device based on long-range surface plasmons [3], where the cross-talk figures are ~ -27 dB (tuned to LP_{11}) and ~ -10 dB (tuned to LP_{01}).

Clearly, the predicted modal selectivity is considerably better in a device based on SGBM's.

Another important parameter is the change in oil index necessary to tune between different fibre modes. Δn_{oil} ~ 0.005 in case of the SGBM and Δn_{oil} ~ 0.016 in case of the WGM, showing that the tunability is more effective in the case of the SGBM, a distinctive advantage in further developments towards an active device. The tunability can be expressed by the rate of change of mode index with oil index, which for the SGBM case is $\Delta n_{SGBM}/\Delta n_{oil} \sim 0.6$, slightly higher than in the plasmon case where $\Delta n_{Pl}/\Delta n_{oil} \sim -0.47$ [3].

In Fig.6 the coupling length for each fibre mode is plotted, employing the multilayer stack (solid lines) and the high-index waveguide (dotted lines). As can be seen, the coupling lengths for the individual fibre modes peak strongly at the corresponding phase-matching points. For the same oil thickness, the coupling to the SGBM is stronger than to the WGM, as indicated by the shorter coupling length.

6. Conclusions

Mode-selective couplers based on SGBM's offer distinct advantages in comparison to devices based on long-range surface plasmons. In particular, good modal selectivity is achievable together with high tunability, and low cross-talk from the higher order fibre mode is maintained when the device is tuned to the fundamental fibre mode. In our calculations, the SGBM is supported by a dielectric multilayer stack consisting of alternating layers of $Al_{0.1}Ga_{0.9}As$ and AlAs. A similar figure of merit combining cross-talk and coupling length is expected for a coupler based on a single-mode planar dielectric waveguide with a core index equal to the average stack index. However, the amount of index change needed to tune between the two fibre modes is about three times less in the case of the SGBM based coupler. This is a distinct advantage for designing a future active device.

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Figure Captions

Figure1: Generic mode-selective fibre coupler (MSFC) geometry.

Figure2: Refractive index profile of the mode-selective coupler employing a) the dielectric multilayer stack and b) the high-index single-mode waveguide.

Figure3: Effective index of the normal modes of the coupler based on SGBM's as a function of the refractive index of the oil layer.

Figure4: Normalized maximum power coupled from each fibre mode as a function of the refractive index of the oil layer, employing the multilayer stack (solid lines) and the high-index waveguide (dotted lines).

Figure5: Cross-talk and coupling length of both fibre modes for the coupler based on SGBM's as a function of the thickness of the oil layer.

Figure6: Coupling length of both fibre modes as a function of the refractive index of the oil layer, employing the multilayer stack (solid lines) and the high-index waveguide (dotted lines).

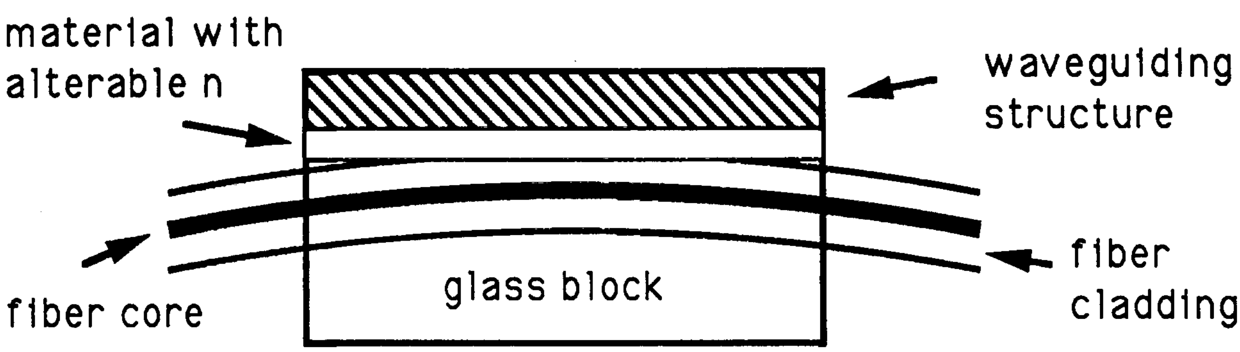

material with
alterable n
waveguiding
structure
fiber core
glass block
fiber
cladding

FIG.1

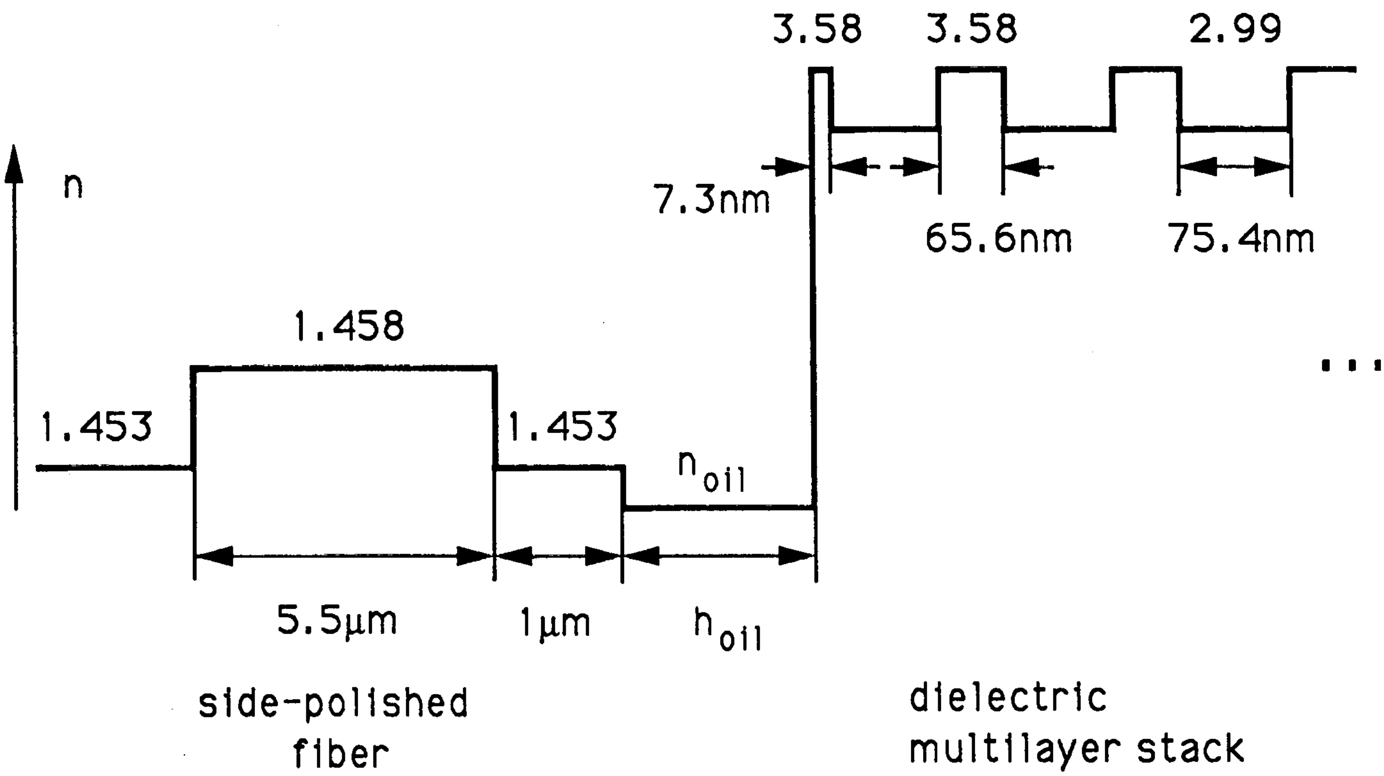

3.58
3.58
2.99
n
7.3nm
65.6nm
75.4nm
1.458
...
1.453
1.453
n_{oil}
5.5μm
1μm
h_{oil}
side-polished
fiber
dielectric
multilayer stack

Fig.2a

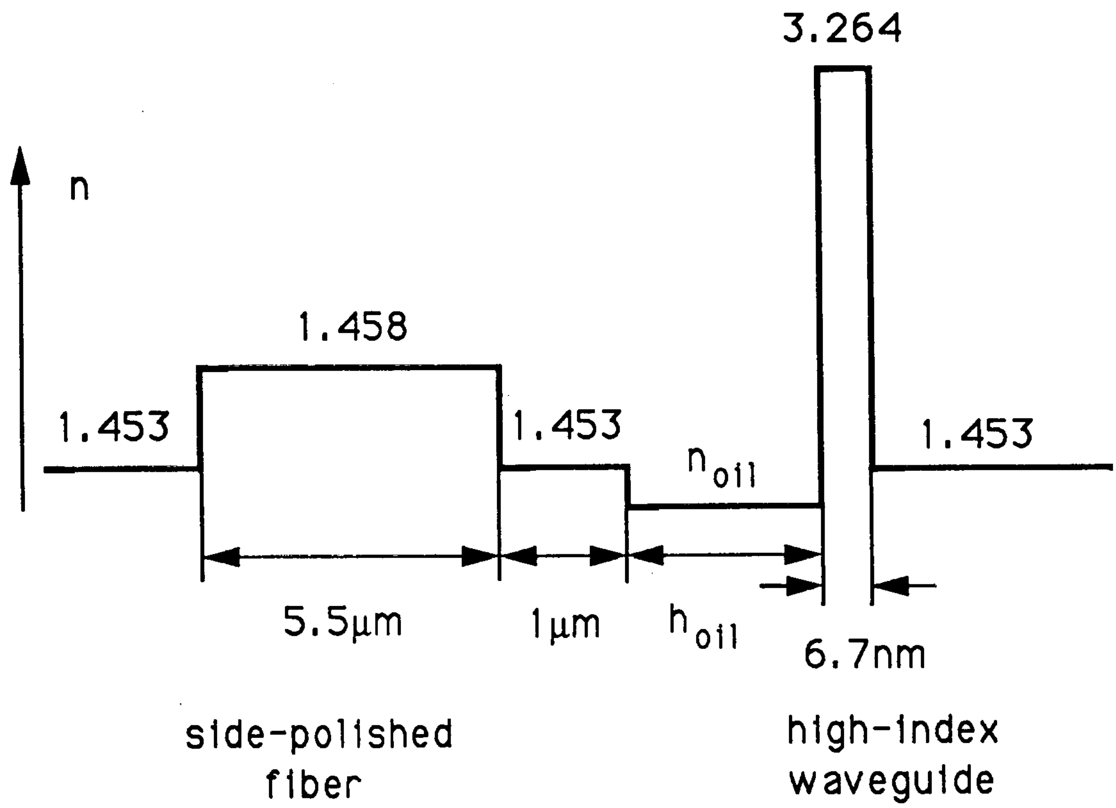

3.264
n
1.458
1.453
1.453
n_{oil}
1.453
5.5µm
1µm
h_{oil}
6.7nm
side-polished
fiber
high-index
waveguide

Fig.2b

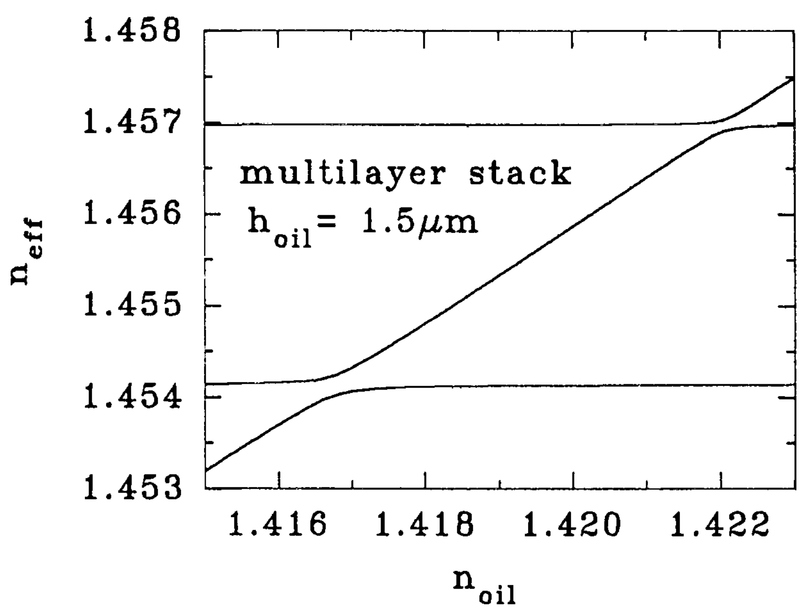
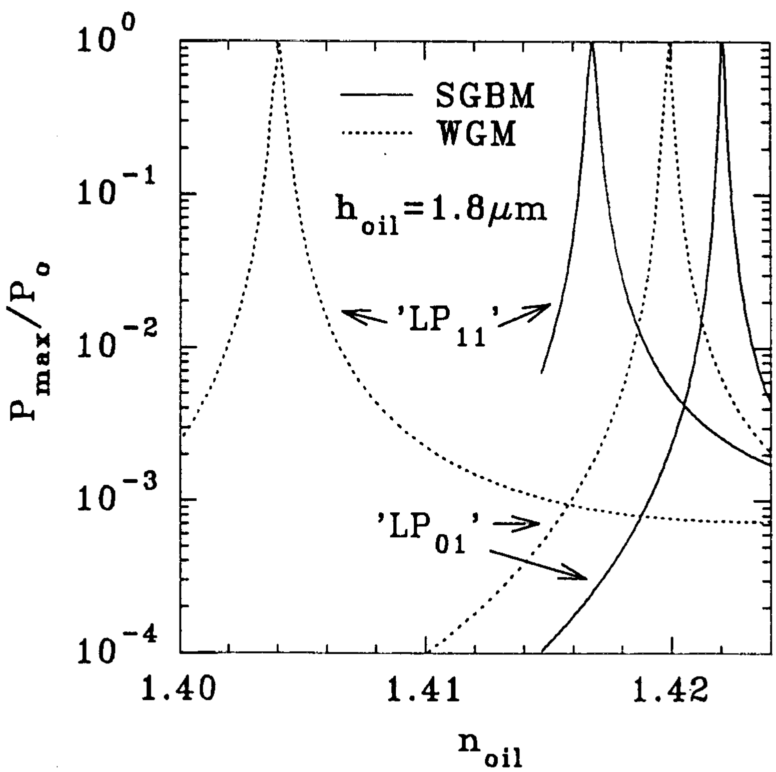

1.458
1.457
1.456
1.455
1.454
1.453
multilayer stack
h oil = 1.5μm
n eff
1.416
1.418
1.420
1.422
n oil

Fig.3



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
P_{max}/P_o
SGBM
WGM
$h_{oil}=1.8\mu m$
'LP_{11}'
'LP_{01}'
1.40
1.41
1.42
n_{oil}

Fig.4

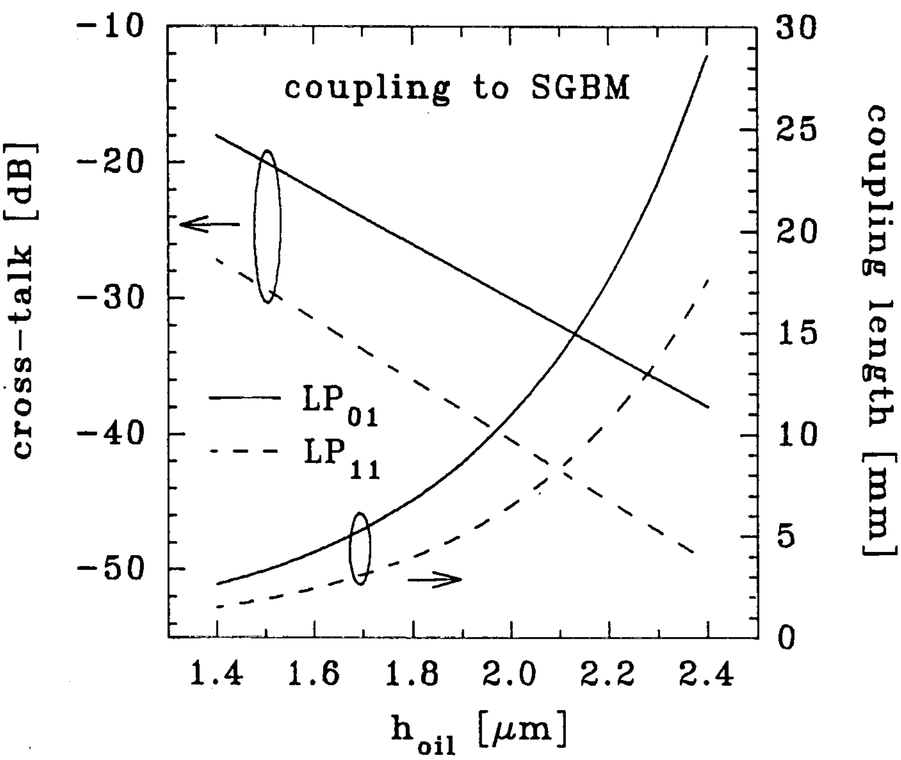

coupling to SGBM
cross-talk [dB]
-10
-20
-30
-40
-50
coupling length [mm]
30
25
20
15
10
5
0
LP01
LP11
1.4
1.6
1.8
2.0
2.2
2.4
hoil [μm]

Fig.5

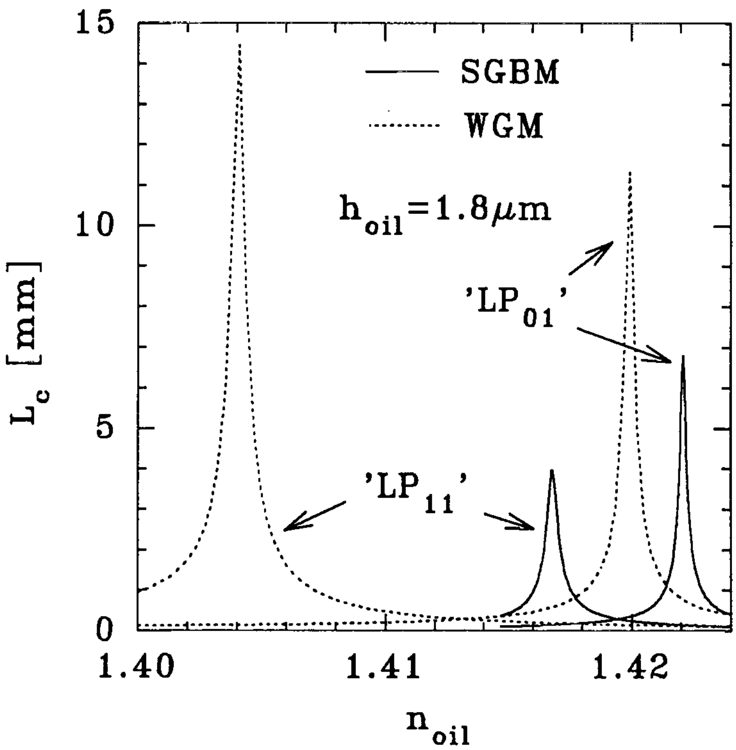


Fig.6