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Selective Excitation of Fiber-Modes Using Surface Plasmons

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Abstract—**Experimental and theoretical results are presented on a surface plasmon fiber device that provides selective excitation of individual modes in a dual-mode optical fiber. Using prism coupling to probe this device, good modal discrimination was obtained experimentally for the LP$_{11}$ fiber mode. The LP$_{11}$ modal discrimination, however, was found to be inherently limited by the field distribution characteristics of the dual-mode fiber. Applications are to fixed and tunable mode tap or couplers.**

I. INTRODUCTION

SURFACE plasmon-polaritons or simply Surface Plasmons (SP's), supported by single metal/dielectric interface or thin-metal-film structures, have been studied extensively both theoretically and experimentally [1], [2]. They have been excited using bulk-optic (attenuated total reflection—ATR), as well as, fiber-optic techniques (side polishing). In both cases, the propagation constant of the excitation beam is carefully adjusted to match to the SP propagation constant, resulting in a resonant energy exchange via evanescent field interaction. In fiber optics, SP's have been mainly used to implement high quality all-fiber polarizers and polarising beam-splitters [3]–[5]. So far, the bulk of SP investigations has been focused on long-range SP's (LRSP's), supported by thin metal films, due to their small propagation losses and long propagation distances (of the order of mm). However, Kou and Tamir [6] have proposed a modified structure, comprised of a thin metal film in close proximity to a single-mode dielectric waveguide, that can support an ultra-low-loss plasmon mode, called extended-range SP (ERSP). To date, this SP mode has not attracted enough attention and no attempt has been made to study it experimentally or use it in a practical device. In this letter, ERSP's supported by a composite thin-metal-film/dual-mode-fiber structure are studied both experimentally and theoretically and their use in tunable selective mode coupling in mode-division-multiplexed fiber systems (modal taps or couplers) is explored. Other techniques have already been studied for this purpose [11], [12], but they do not yield tunable mode selection.

II. DEVICE DESCRIPTION AND EXPERIMENTAL SET-UP

The device under investigation can be seen schematically in Fig. 1. A dual-mode (at 632.8 nm) step-index optical fiber was mounted in a curved groove made on a glass block and part of its cladding removed by the side-polishing technique [7] in order to access the evanescent field of the propagating modes. The groove had a curvature radius of 1.3 m, which resulted in interaction lengths of 1.49 mm and 1.85 mm for the LP$_{01}$ and LP$_{11}$, respectively [7]. A thin silver film was then evaporated on the polished fiber surface. A layer of refractive-index liquid was placed on top to serve as a buffer layer between the thin metal film and an overlaid high refractive index prism. The composite waveguiding structure, therefore, consisted of a thin silver film brought in close proximity to a dual-mode fiber. The various composite eigenmodes were excited by evanescent field interaction and phase matching with the totally-internally-reflected (TIR) incident He–Ne laser beam. The effective propagation constant of the excitation beam was controlled by varying the angle of incidence at the base of the high-index prism (steps of 0.002°). The dual-mode fiber parameters were: $n_{\text{core}} = 1.4707$, $n_{\text{clad}} = 1.457$ and core diameter $= 3.4\ \mu$m.

The device was placed on a turn-table that was accurately controlled by a computer (Fig. 1). The set-up was arranged so that the spot of the excitation beam was kept almost stationary at the prism base when the angle of incidence was varied [8]. The reflected beam was detected by a photodiode placed on a double-speed stage attached to the turntable in order to allow stationarity between detector and reflected light. The power coupled into the two fiber modes (namely, the LP$_{01}$ and LP$_{11}$ modes) was monitored by a second photodetector.

III. EXPERIMENTAL RESULTS

Several dual-mode fiber devices were prepared and the mode excitation efficiency tested. Different polishing depths, silver film thicknesses and buffer liquid indices were tried. The mode excitation efficiency in the case without metal film was also measured for comparison. In the absence of a metal film, light can couple directly into each fiber mode by choosing the appropriate prism coupling angle. In the presence of a metal film, however, only the fiber mode that is phase matched to the LRSP mode supported by the thin metal film in isolation is strongly excited. The fiber mode mismatched to the LRSP can also be weakly excited and this depends on the degree of the field overlapping between them.

Fig. 2 shows the photodiode signals of the coupled light as the effective index (n_{eff}) of the excitation beam varies, where $n_{\text{eff}} = n_p \sin\phi$, n_p is the prism index and ϕ is the angle of incidence at the prism base (measured to its normal). The thickness of the oil layer is $h_{\text{oil}} \sim 1\ \mu$m and

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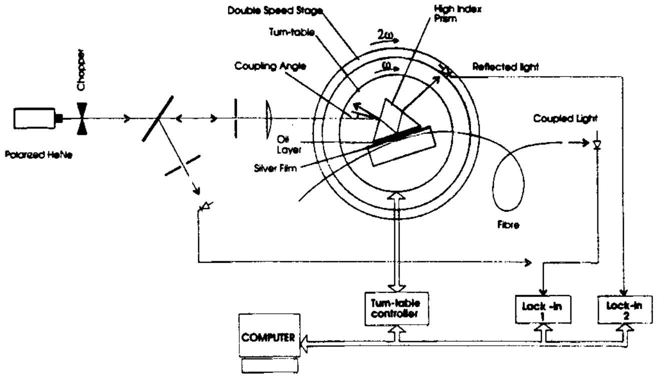


Fig. 1. Prism-coupling characterization set-up. The fiber mode selective coupling device is also shown in this figure.

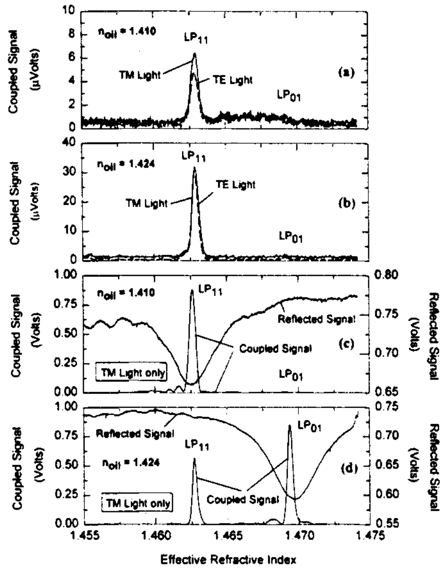
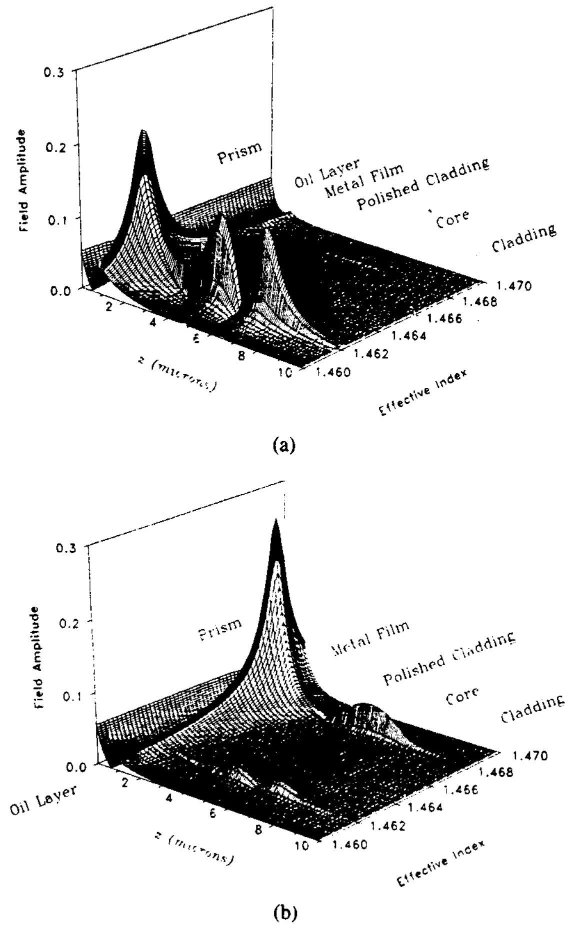


Fig. 2. Experimental prism-coupling to a side polished dual-mode fiber without silver film [(a) and (b)], and with a 26-nm (h_m) thick silver film on top of the polished cladding [(c) and (d)], for oil indices of 1.410 and 1.424, respectively. $h_{\rm oil} \sim 1$ μm, $h_{\rm cl} = 2$–3 μm in all cases. The LRSP matches to the LP_{11} mode in (c) and to the LP_{01} mode in (d), respectively. The TIR light is also shown in (c) and (d).

the cladding thickness remaining after polishing is $h_{\rm cl} = 2$–3 μm (representing 4 dB attenuation in the oil-drop technique [9]). Fig. 2(a) and (b) corresponds to the case without silver film, for oils of refractive index 1.410 and 1.424 respectively. Although a small polarization dependence is observed for the lower index oil, Fig. 2(a)—corresponding to a larger oil/cladding index difference, the coupling strength of TE and TM polarized beams are found to be quite similar and very small. In both figures, the LP_{11} is excited more strongly than the LP_{01} mode due to the longer field penetration. The measured intensities of the TIR light (not plotted) did not show any noticeable dip. Fig. 2(c) and (d) corresponds to the case with a 26-nm silver film deposited on top of the polished fiber and the same oils as Fig. 2(a) and (b). In Fig. 2(c), the index of the oil buffer layer ($n_{\rm oil} = 1.410$) was chosen to match the LRSP to the LP_{11} mode. In this case, TM-polarized light couples strongly to LP_{11} with only a small amount (-18 dB) coupling to LP_{01}. A comparison of Fig. 2(a) and (c) shows a huge difference in the signal levels. This is because the energy transfer between prism and fiber is resonantly enhanced by the excitation of the ERSP mode. In Fig. 2(d), the $n_{\rm oil}$ is 1.424 and the LRSP now matches the LP_{01} fiber mode. Although, the LP_{01} is strongly excited, as anticipated, there is some unwanted excitation of the LP_{11} mode as well. This is explained in the next section, with reference to Fig. 3(b). In Fig. 2(c) and (d), the TIR light is also plotted. The measured ATR dip is associated only with the excitation of the LRSP wave supported by the thin metal film. This is because the ratio of the LRSP effective area to the focused incident beam spot size is of order of 125/400, whereas the ratio of spot sizes of the excited ERSP mode to the focused incident beam is of order of 5/400. Therefore, the excitation of the ERSP waves (supported by and localized around the fiber core) does not perturb considerably the amount of reflected light and, thus, does not show in the ATR plots. To describe the efficiency of modal excitation, we introduce the modal discrimination parameter ($MD_{01(11)}$) defined as the ratio between the $LP_{01(11)}$ peak intensity and sum of the LP_{01} plus LP_{11} peak intensities. In Fig. 2(c), $MD_{11} = 99\%$ while in Fig. 2(d), $MD_{01} = 60\%$. No detectable coupling of TE-polarized light was observed (< -30 dB), due to the inherent high polarizability of surface-plasmons [1]–[6].



(a)

(b)

Fig. 3. Magnetic field distribution $|\vec{H}_y(z)|$, arbitrary units, versus effective index of the incident beam for: (a) LRSP matching LP_{11} waveguide mode ($n_{\rm oil} = 1.415555$) and (b) LRSP matching LP_{01} waveguide mode ($n_{\rm oil} = 1.428425$). The theoretical model assumes $\lambda = 632.8$ nm and the equivalent slab structure as follows: $n_p = 1.79883$, $h_{\rm oil} = 1$ μm, $\epsilon m = -17.5 + j\,0.7$, $h_m = 26$ nm, $n_{\rm cl} = 1.457$, $h_{\rm cl} = 3$ m, $n_{\rm core} = 1.4707$, $h_{\rm core} = 2.85$ m.

IV. THEORETICAL RESULTS

The theoretical model was obtained by solving the Maxwell's equations (TM case) and applying the boundary conditions to the equivalent slab structure (6 planar layers) of the device, which led to a complex-eigenvalue problem of 10 linear equations. The dual-mode fiber was represented by an equivalent dual-mode planar waveguide whose propagation constants were designed to closely approximate the fiber-mode ones. Three eigenmodes were found, which are related to the combinations of the LRSP with the two fiber modes: one composite long-range mode whose power is mainly in the metal film (C-LRSP) and two extended-range modes (LP_{01}-like and one LP_{11}-like) whose power is primarily in the dielectric waveguide ($ERSP_{01}$ and $ERSP_{11}$).

Fig. 3 shows the total magnetic field distribution in the structure as a function of the effective index of the excitation beam (considered to be of constant power) and takes into account the three eigen-modes. In Fig. 3(a), the n_{oil} was 1.415555 so that the LRSP matches to the LP_{11} mode of the dielectric waveguide. The LP_{01}, on the other hand, is hardly observed, in excellent agreement with the experiments [cf. Fig. 2(c)]. In Fig. 3(b), n_{oil} was 1.428425 so that the LRSP/LP_{01} matching was occurring. As in the experiments, some unwanted excitation of the LP_{11} mode was observed. From the experimental and theoretical results, it is shown that the device can provide excellent selective excitation of the LP_{11} (higher order) mode by adjusting the buffer-layer refractive index. However, variation of this refractive index to achieve LP_{01} (lower order) mode excitation is always accompanied by unwanted excitation of the LP_{11} mode. The later occurs because although the LP_{11} is phase-mismatched to the LRSP, it penetrates deeper into the cladding resulting in stronger overlapping with the LRSP and sizeable excitation.

Finally, the slab structure was analyzed for best possible modal discrimination within the known constraints. The optimum polished cladding thickness h_{cl} was then found to be 3.0 μm and the best oil indices n_{oil} were 1.428425 for LP_{01} selection and 1.415555 for LP_{01} selection, providing modal discriminations $MD_{11} = 99.8\%$ and $MD_{01} = 91.2\%$. The device length (propagation length) was between 0.5 and 1.0 mm in order to keep a good trade-off between losses and discrimination. The best insertion loss was found to be around 0.3 dB and 1.5 dB when selecting the LP_{01} and the LP_{11} modes, respectively. The oil indices that provide LRSP/LP_{11} and LRSP/LP_{01} matching, although slightly higher, were in good agreement with the experiments. This results from the uncertainty (±3 nm) in determining exactly the film thickness as well as from the planar approximations in the model.

V. CONCLUSION

Surface plasmons were used to excite selectively modes of a dual-mode fiber. Tunable modal selectivity was achieved by varying the buffer layer refractive index ($\Delta n_{\text{buffer}} = 0.014$). It was shown both experimentally and theoretically that higher order modes (LP_{11}) can be excited with good discrimination. However, excitation of the lower-order modes suffers from concomitant excitation of unwanted higher order modes and, therefore. shows smaller discrimination. The theory predicts that the overall performance of the device can be improved by optimizing the various parameters. A practical all-fiber device can be implemented by replacing the bulk prism by another polished fiber [4]. It can also be used as a mode coupler by selecting an appropriate buffer layer refractive index so that only the higher-order mode (LP_{11}) is out-coupled efficiently. The cross-talk in the tunable device can be compensated electronically in the receiver [10] or, alternatively, the unwanted coupled LP_{11} can be stripped out after the device by using standard "oil-drop technique" [9] or by simply bending the fiber. Because of the TM polarizability of surface-plasmons, a polarization adjustment must be done in the device input. Dielectric films can replace the thin metal film in selecting fiber modes, which might lead to lower losses, sharper resonances and better modal discriminations [11]. However, because SP dispersion is much more sensitive to refractive index variations of the adjacent dielectric media, the metal film device requires smaller index variations for tuning than the dielectric film one.

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