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Removing the directional degeneracy of LP_{11} mode in a fused-type mode selective coupler

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***Abstract*—The removal of polarization and modal degeneracy in the excitation of higher order modes is realised in all-fiber mode-selective weakly-fused-couplers by controlling the coupler geometry. Experiments carried out with short couplers showed strong polarization dependency, while long couplers with a slow varying cross-section have shown to remove polarization and spatial degeneracy in the first high order mode.**

***Index Terms*—Couplers, Modal Coupler, Polarization maintaining, Microfibers.**

I. Introduction

IN the last few years, interest in few modes fibres (FMF) has grown quickly, mostly due to their potential use in broadband, high capacity optical networks [1], [2]. The use of FMFs to transfer data allows to increase the bandwidth capacity by a factor equal to the number of the supported modes as each higher order mode (HOM) serves as an isolated channel with capacity comparable to the fundamental mode [3]. Mode-division multiplexing (MDM) has been proposed as an efficient way to exploit HOMs for telecom systems. Multimodes devices such as the mode multiplexer/demultiplexer (MUX/DMUX) are essential components for the MDM systems. Different devices have been investigated to efficiently excite HOMs, including photonic lanterns and mode selective couplers. A photonic lantern is a device fabricated by tapering a number of single mode fibres (SMFs) which are fused together and cladded with a fluorine-doped silica capillary before being spliced to a single FMF. In such configuration each of the modes of the FMF will be a linear combination of modes of the different SMFs and could be decomposed in the original SMF fundamental modes at the photonic lantern output [4]–[7]. An interesting approach relies on the use of asymmetric planar Y-junction splitters/combiners, which combines several independent fundamental mode inputs into specific low order modes of a FMF. This device can be operated as a splitter, where a low order mode in the FMF can be separated into fundamental modes at different outputs [8], [9]. Another promising technique for mode conversion is the tapered velocity mode selective coupler, which is particularly attractive since it does not rely on precise phase matching conditions such as index contrast and coupler geometry [10]. In mode selective couplers (MSC), the fundamental mode of a SMF is coupled with a single HOM in the FMF by phase matching the fundamental mode (FM) and the HOM in dissimilar diameter fibres [11], [12] ((Fig. 1)). The fabrication of MSC was implemented in the form of polished couplers [13], fused etched couplers [14], [15] and weakly fused couplers [16]. The excitation of the HOMs in a weakly-fused coupler (WFC) composed of a standard SMF and a FMF was demonstrated in [16]. The fabrication of modal couplers has also progressed in integrated optics using the femtosecond laser direct-write technique in a boro-aluminosilicate glass chip [17], [18] and planar lightwave circuit (PLC) based technology involving mode rotation [19]. Ultra-broadband mode multiplexer showed low loss multiplexing of the LP_{01}, LP_{11a} and LP_{11b} over a wide wavelength range [17], [18]. A mode rotator using silica-based PLC demonstrated the successful conversion of the LP_{11a} into the LP_{11b} over a wide wavelength range from 1450 nm to 1650 nm [19]. Although several publications studied the excitation of orthogonal mode orientation in mode selective couplers using three-core configuration in Y-junction coupler [17], [20], to date, no experimental discrimination of spatially- or polarization- degenerate modes has been presented for fused couplers of two single core fibres. In this paper we demonstrate the possibility of selectively excite one single spatial component of a HOM with a selected polarization.

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II. Mode Selective Couplers

WFCs are constituted by two micrometer-diameter tapered fibers joined together and therefore maintain a cross-section similar to the sum of the two dissimilar fibers forming the coupler. This is essential for the complete power transfer between the SMF fundamental mode and the FMF high order mode. The main difference between the WFC and the conventional coupler is the processing temperature, as the latter usually requires a high fusion temperature which leads to an almost circular cross section. Since the FMF usually has a larger numerical aperture and a bigger core diameter than the SMF, the propagating modes in the FMF have effective index higher than the modes propagating in the SMF. When the fibres are tapered to micron size diameters, they are called microfibres (MFs) and their modes are index guided by the silica-air interface, thus both the core size and numerical aperture have minimal effect on the mode effective index. Therefore, matching modes of different MFs implies matching their propagation constants by using different MF diameters [16].

Fused couplers have been used to demonstrate efficient and lossless coupling to all HOMs in the FMF [16]. Yet, The presence of spatial and polarization degeneracy between HOMs has proved to induce losses as well as cross-talk between

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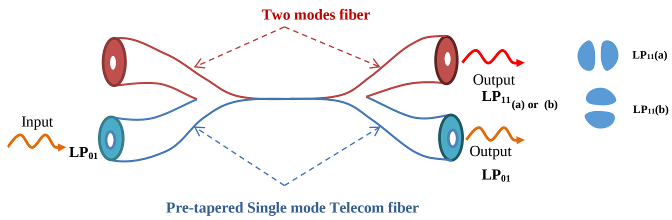

Fig. 1. Schematic of the MSC, composed of a two mode fibre (TMF) and a single mode fibre (SMF). The SMF is pre-tapered to a diameter at which its fundamental mode (LP_{01}) phase matches the higher order mode ((LP_{11}) in the TMF. The output of the coupler is a mixture of two spatial modes ((LP_{11}(a)) and ((LP_{11}(b))

the different channels of a MDM system. It was proved that is possible to overcome this issue by using offline coherent multi input/multi output (MIMO) DSP and high-performance mode couplers based on phase plates [2]. However, communication systems in general, and MDM specifically, still require generating higher order modes in one specific spatial direction with high modal purity. As modal and polarization degeneracies arise from the cylindrical symmetry of optical fibres, because of the lack of azimuthal symmetry, modal couplers are expected to support modes that are directional and show polarization dependence [21], [22], i.e. HOMs with different polarizations or spatial field distribution (Fig. 2) exhibit a different effective index. Here the excitation of a selected spatially-non-degenerate LP_{11} mode is demonstrated by increasing the difference between the effective indices of the two orthogonal modes which are degenerate in a cylindrically symmetric waveguide.

III. Principle Of Operation

Mode-selective couplers composed of closely-positioned fibers were theoretically analyzed in [20] with port (1-3) is the through port, the input and the output belonging to the same SMF fiber. (Port 1-4) is the coupled port and represents the output at the TMF when the input is in the SMF. They rely on the phase-matching of a higher-order mode in one fiber with the fundamental mode of a second fibre. The power transfer between the coupler arm is dependent on the azimuthal mode number of the higher-order mode, as well as its spatial-orientation [20], [23]. Despite the symmetry of the field distribution in the couplers, it is possible to couple the modes between the two adjacent fibers forming the coupler, because the structure of the coupler breaks the orthogonality between the two modes. As modes do not share the same center (they are in different fibers), the overlap integral of the fields of the two modes is not equal to zero, and therefore coupling takes place [24], [25].

Couplers made from optical fibres with dissimilar diameter, the propagation constant β_1 of the fundamental mode in the tapered SMF is phase matched with the β_2 of the high-order mode in the tapered FMF, thus the phase mismatch $\Delta\beta = \beta_1 - \beta_2$ is zero and the power distribution across the two tapered fibres forming the coupler reduces to $P_1(z) \propto \cos^2(\kappa z)$, $P_2(z) \propto \sin^2(\kappa z)$ indicating a complete periodic power transfer between the two MFs in the lossless case. κ is the coupling coefficient which depends on the refractive index profile and the cross-section geometry. Any change in the fibre size or in the surrounding refractive index introduces a nonzero phase mismatch $\Delta\beta \neq 0$ which limits the fraction of the input power coupled into the higher-order mode.

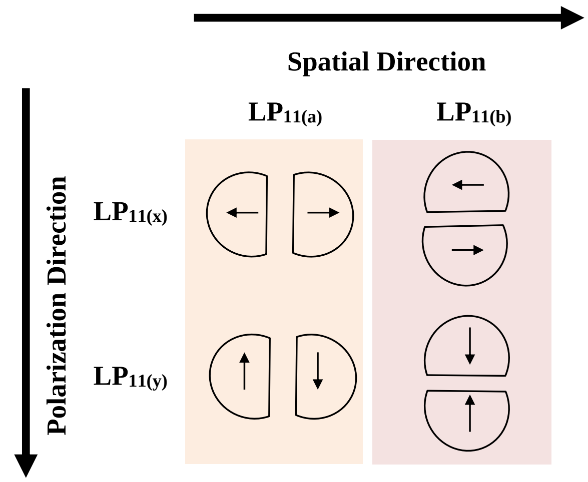

Fig. 2. Polarization directions and spatial components of the LP_{11} mode.

It is well known that the LP has two components in the vertical and horizontal spatial directions that are denoted $LP_{11(a)}$ and $LP_{11(b)}$ respectively. For each spatial direction the mode has two polarizations (x and y) as shown in Fig. 2. The polarization discrimination capability of the coupler results from the coupler weakly fused cross section, which does not have a cylindrical symmetry and thus supports $LP_{11(a)}$ and $LP_{11(b)}$ with different β. As the phase difference between modes is the product of effective index difference times length, in order to separate the two HOM spatial modes with distinct but close effective index, the coupler uniform waist region should have a long coupling length, enough to have a $\Delta\beta$=$\pi/2$ between the $LP_{11(a)}$ and $LP_{11(b)}$ modes at the end of the coupling region.

In order to achieve the phase matching between the LP_{11} in the FMF and the LP_{01} in the SMF, it is essential that both modes have exactly the same effective index, and since the modes have a different overlap with the core, the diameter of one of the fibres was varied to get equal effective indices (and therefore equal propagation constants) of the matched modes. The output spectra of a weakly fused coupler were simulated using the methodology explained in ref. [16] and parameters from a commercially available SMF (Elliot Scientific, SMF-$1300/1500 - 8.2/125 - 0.25 - L$, core/cladding diameter $= 8.2/125\mu$m, $NA = 0.14$) and a FMF (core/cladding diameter $= 19.7/125\mu$m, $NA = 0.12$) at $\lambda = 1.55\mu$m. The simulations were carried out using a commercial finite element software (COMSOL multiphysics) to determine the dependence of the effective refractive index of the different modes propagating in tapered SMF and FMF fibres at different fibre diameters. The mesh size and the width of the perfectly matched layers were made variable depending on the diameter of the tapered fibre.

Fig. 3(a) shows that at diameter around 11μm the LP_{11} in the TMF will have an effective index (n_{eff}) of 1.435 while the LP_{01} in the SMF will also have the same effective index at diameter of around 6.952μm. This mean that the SMF should be smaller than the FMF by a ratio of 0.632, in order to match the two modes in the two fibres. The phase matching curves (Fig. 3(a)) indicate that the SMF should be pre-tapered to a diameter of 79 μm to phase match to the LP_{11} mode in the FMF.

The weakly fused coupler was manufactured using the modified flame brushing technique at a processing temperature T< 1400^{o}C. The coupler profile at the waist region was analysed under a scanning electron microscope (SEM) to calculate the effective indices of all LP_{11} modes with orthogonal spatial and polarization direction by using the finite element method explained above. Fig. 3(b) shows that there is indeed a small difference between the mode effective indices for different polarization directions ($LP_{11(x)}$,$LP_{11(y)}$), while a noticeable difference occurs for modes in orthogonal spatial distribution (LP_{11a},LP_{11b}). It is clear from Fig. 3(b) that modes in different spatial directions have different propagation constants, and therefore it is possible to separate these spatial modes at specific lengths of the coupler. Since the phase difference accumulates along the coupler uniform waist region, a long coupler allows for the selective excitation of one single mode with a determined spatial direction. Despite that the coupler is weakly fused, the fused section between the two fiber plays a vital role in the distribution of the modal field in the cross-section. Modeling showed that a small degree of fusion would allow the $LP11_{b}$ (Fig. 3(b)) to spread along the transverse direction of the coupler, and the field in this instance can not be approximated with the field generated by two closely placed fibers.

To estimate the required coupler length, the effect of elongation during fabrication (thus length of the coupling region) on the coupling coefficient was examined assuming that the cross section remained constant in the down- and up-taper regions. After finding the values of the varying coupling coefficient, it was possible to calculate the dependence of coupler transmission on the elongation as shown in Fig. 3(c). The length of the coupling region at which the first cycle of power exchange occurs was found to be 20mm.

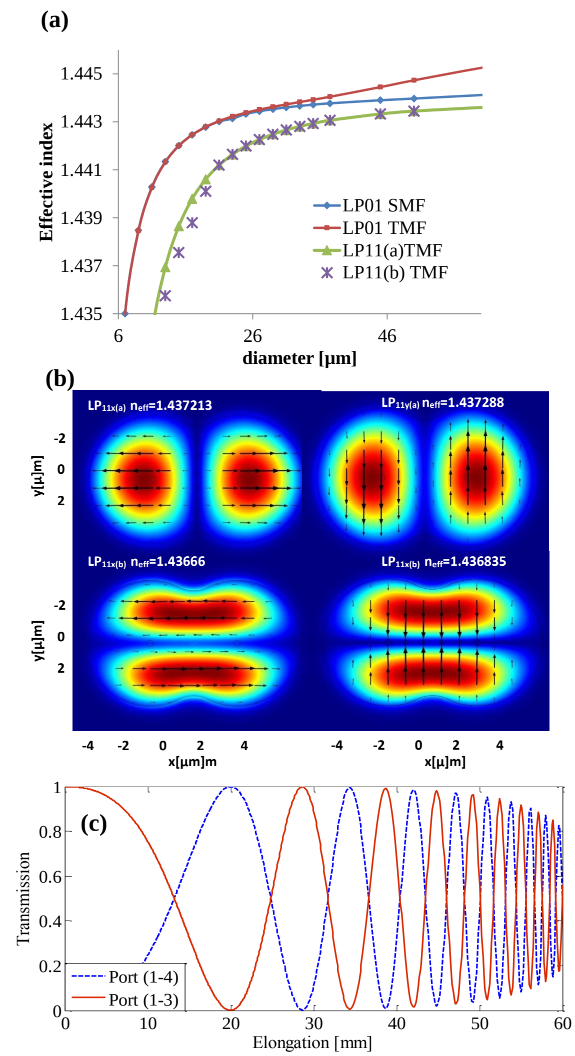

Fig. 3. (a) Dependence of the effective refractive index of the fundamental LP_{01} and first high order mode LP_{11} on the diameter of the tapered fibre in single mode fibre (SMF) and a few mode fibre supporting only two modes (TMF). (b) Effective index and mode field distribution of the different spatial and polarization components of the LP_{11} mode. (c) Coupler output power for different values of the coupling length; the operation wavelength and diameter of the coupling region were $\lambda = 1.5\mu$m and $d_c = 9\mu$m, respectively.

IV. Experiment

Two WFCs were manufactured to determine the polarization dependence/selectivity. the coupler consist of four ports; port (1-3) is the through port, the input and the output belonging to the same SMF fiber. (Port 1-4) is the coupled port and represents the output at the TMF when the input is in the SMF. The coupler lengths were $L = 2$cm in coupler 1 and $L = 5$cm in coupler 2. In both couplers the SMF diameter was pre-tapered to 79 μm. Insertion loss was smaller than 0.1 dB in both devices. The pre-tapered fiber was then aligned with a TMF (using some adhesive material) and fused together using the modified flame brushing technique [26], [27]. Temperature was decreased gradually when approaching the final diameter. The speed of tapering was also varied through the tapering to maintain the shape of the coupler cross-section. Tapering was performed using high precision computer controlled stages. The tapering variable speed was controlled by a code allowing fast tapering at the beginning of the process and slow tapering towards the end. It was noticed that twisting the two fibers prior tapering, would influence the mode purity and conversion efficiency considerably, since twisting would rotate the fields in each fiber periodically (depending on the twisting angle and number of turns) and hence complicate the modal conversion. The power transfer between both fibres was monitored in-situ using a power meter attached to both output ports, while light from a laser diode source was launched into a linear polarizer which was then connected to the SMF input port. The output of the TMF was monitored during the process and tapering was stopped when most of the power reached the coupled port (the TMF arm of the coupler).

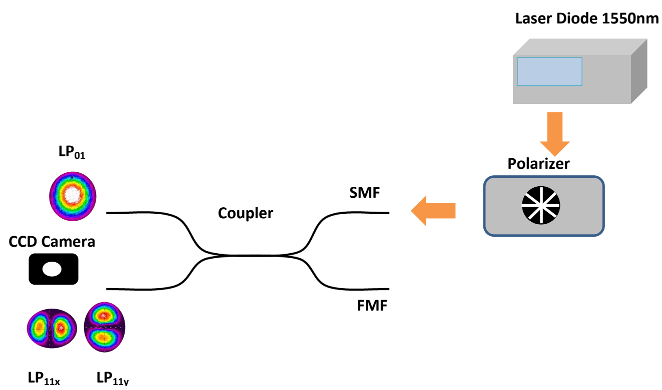

Fig. 4. Experimental set-up to monitor the spatial mode distribution in modal couplers.

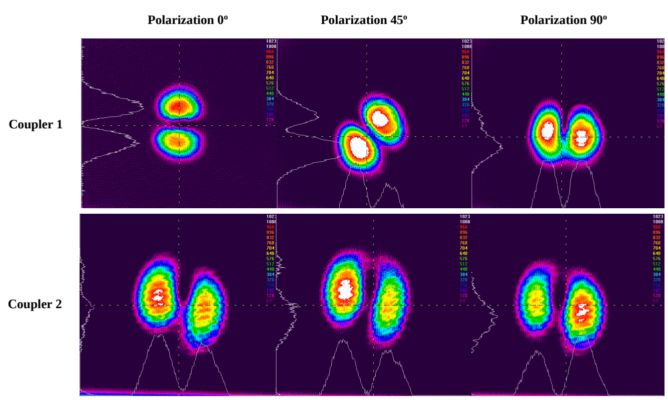

Fig. 5. Far field images of the LP_{11} mode for coupler 1, coupler 2 at both polarization directions.

The spatial intensity distribution for different polarizations at the coupler output was monitored at $\lambda = 1.5\mu$m using the set-up shown in Fig. 4. Light from a laser diode emitting at $\lambda = 1550$nm was injected into the SMF port of the coupler after traveling through a polarizer. The TMF output port was then monitored using a CCD camera. Fig. 5 shows that the 2 $\sim$cm long coupler (coupler 1) successfully converted the fundamental SMF mode into the TMF HOM. The same figure also shows that the coupling is highly polarization dependent. A polarization rotation of the incident light by 90 $^\circ$ caused the mode spatial profile captured by the CCD camera to rotate by 90 $^\circ$. The spectrum at the coupler TMF output port was also monitored using an optical spectrum analyser (OSA) for both spatial direction (Fig. 6). The recorded insertion losses were 3.7dB for the LP_{11a} (0 $^\circ$) and 5.1dB for the LP_{11b} (90 $^\circ$).

Coupler 2 exhibited a total insertion loss smaller than 0.1dB, and the LP_{11} was obtained with high efficiency ($> 97\%$). its clear that the loss observed in coupler 1 is considerably higher than that in coupler 2. It is believed that coupler 1 guides the two spatial component of the higher order mode LP_{11}, thus it is possible to expect some loss when the polarizer is inserted, as the polarizer removes one of these spatial modes which carry part of the power guided by the coupler. The polarization dependency was monitored using the same system and seems to be less pronounced. The TMF port output of coupler 2, shown in Fig.5, shows that rotating the polarizer has a minimum effect on the spatial field distribution. This seems to indicate that coupling occurs only with only one spatial mode. i.e. the spatial degeneracy has been removed. Moreover, no major change was noticed in the spectrum of the TMF arm for both spatial directions. This behaviour of the long coupler is attributed to the increased phase accumulated in the coupler by the modes in the orthogonal spatial directions ($LP_{11a} \neq LP_{11b}$), which resulted from the geometry of the asymmetric coupler cross-section. The mode profile captured by the camera is not affected by the change of the polarization direction, since only the mode in one spatial direction was collected at the coupler TMF output port.

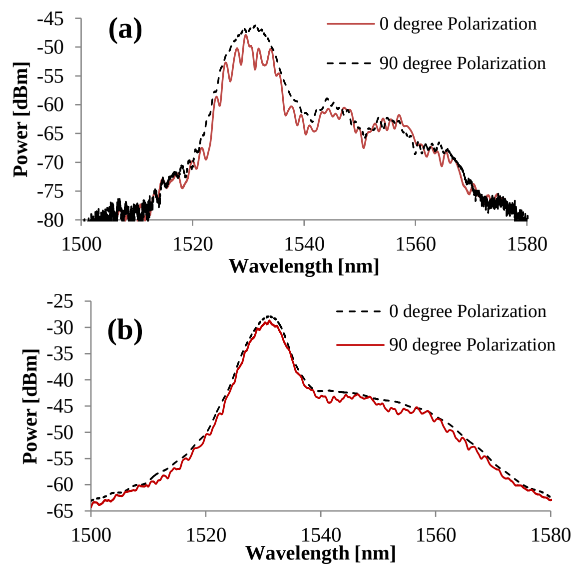

Fig. 6. Spectrum at different polarizations for (a) the short coupler (coupler1) and (b) the long coupler (coupler2)

The different operation behavior of short (coupler 1) and long (coupler 2) couplers were noticed experimentally with high repeatability. While short couplers always exhibited mode orientation dependence on the polarization input, long couplers can be unaffected by polarization azimuth change. One possible explanation is that the length of coupler 1 is not enough to discriminate the two degenerate spatial modes LP_{11a} and LP_{11b} supported by the coupler, while in the longer waist coupler, the slight difference in the propagation constant of the LP_{11a} and LP_{11b} can produce a $\pi/2$ phase shift needed to remove the degeneracy between the two spatial modes, resulting in a single spatial mode being excited at the coupler output

Fig. 7 shows the coupling efficiency at different wavelengths around the telecom wavelength 1550nm. It was noticed that most of the power was coupled to the higher order mode LP_{11} in the TMF arm of the coupler, while less than 5% of the power remained in the SMF arm. The LP_{11} mode extinction ratio compared to the LP_{01} was over 90% over the wavelength range measured.

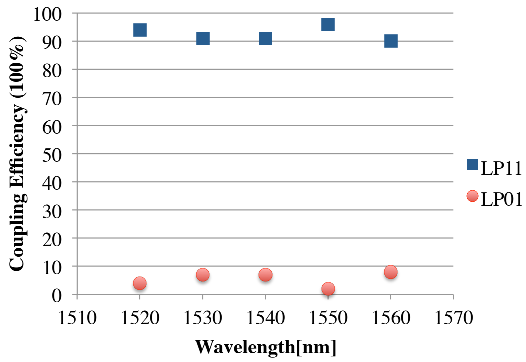

Fig. 7. Recorded coupling efficiency at different wavelengths. The coupler shows high coupling efficiencies over 40nm wavelength range around the telecom wavelength.

The manufacturing of the proposed coupler is a straightforward and highly reproducible process. Although the selective excitation of higher order modes is found to be highly repeatable, the coupler conversion efficiency is critically dependent on the coupler cross-section. The repeatability of the process is dependent on the phase matching diameter, on the coupler length and on maintaining the coupler weakly fused cross-section, which can easily be achieved by adjusting the tapering speed. It is fair to say that the proposed coupler can be manufactured with high accuracy, similar to planar technologies such as femtosecond laser direct write [18] and PLC-based integrated technologies [19].

V. Conclusions

In summary, efficient generation of a selected spatially and polarization distinct higher order mode LP_{11} was achieved using a simple mode selective coupler. Modelling and experiments were performed to determine the polarization dependence of the coupler. The two spatial components of the mode were successfully separated. The polarization dependency of the coupler was also analysed, showing that it is possible to separate degenerate spatial modes.

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