Manufacturing and characterization of asymmetric evanescent field polished couplers for grating assisted mode selective fiber coupling

Sebastian Schlangen, Kort Bremer, Yulong Zheng, Andreas Isaak, Marc Wurz, et al.

Sebastian Schlangen, Kort Bremer, Yulong Zheng, Andreas Isaak, Marc Wurz, Sebastian Böhm, Felix Wellmann, Michael Steinke, Gabriel Pelegrina Bonilla, Jörg Neumann, Dietmar Kracht, Bernhard Roth, Ludger Overmeyer, "Manufacturing and characterization of asymmetric evanescent field polished couplers for grating assisted mode selective fiber coupling," Proc. SPIE 10681, Micro-Structured and Specialty Optical Fibres V, 1068116 (9 May 2018); doi: 10.1117/12.2306772

Event: SPIE Photonics Europe, 2018, Strasbourg, France

Manufacturing and characterization of asymmetric evanescent field polished couplers for grating assisted mode selective fiber coupling

Sebastian Schlangen[a,*], Kort Bremer[a], Yulong Zheng[a], Andreas Isaak[b], Marc Wurz[b], Sebastian Böhm[c], Felix Wellmann[c], Michael Steinke[c], Gabriel Pelegrina Bonilla[c], Jörg Neumann[c], Dietmar Kracht[c], Bernhard Roth[a], and Ludger Overmeyer[a,c]
[a]Hannover Centre for Optical Technologies, Leibniz University Hannover, Hannover, Germany
[b] Institute of Micro Production Technology, Leibniz University Hannover, Garbsen, Germany
[c] Laser Zentrum Hannover e.V., Hannover, Germany
* Corresponding author: Sebastian.schlangen@hot.uni-hannover.de

Abstract

Mode division multiplexing (MDM) could bring a technological progress in the field of optical telecommunication by increasing the data transmission bandwidth. A key challenge for enabling MDM lies in manufacturing of efficient and cost-effective mode–selective fiber couplers. The fiber grating based mode selective coupling approach is a method that is currently being under research in this context. In this work a novel process for manufacturing of asymmetric evanescent field polished couplers is presented which enables grating assisted mode selective coupling. In addition, we discuss the optical setup developed for characterization of these couplers.

Keywords: mode selective fiber coupler, polished fiber coupler, fiber grating, mode division multiplexing, space division multiplexing

1. Introduction

In fiber optic telecommunication, different multiplexing technologies such as Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) have successfully been applied in order to increase the transmission capacity of standard single mode fibers. However, in order to keep up with the rapidly increasing demand for transmission bandwidth in the future, research into new optical multiplexing technologies, such as Spatial Division Multiplexing (SDM), is currently being undertaken [1]. SDM is based on increasing the data transmission capacity of optical fibers either by using multi core fibers [2] or few mode (fm) fibers. In case of fm fibers, the fiber core itself is increased so that only a small number of modes can be excited and guided [3]. Each guided mode of the fm fiber then corresponds to an individual transmission channel. As MDM can be combined with TDM and WDM, the data transmission can be increased proportional to the number of guided modes in comparison to single mode (sm) fiber transmission systems using WDM, TDM or both. Based on MDM approaches data transmission capacities of 3.8 Tb/s could be achieved [3].

A key challenge to realize MDM is the development of fiber couplers which enable selective coupling between various modes of the fm fibers and the sm fiber fundamental mode.

Different coupler approaches to enable MDM were proposed in the literature. For example, one approach is the so-called phase mask method [4,5], where the mode field distributions are generated by spatial light modulators. However, in this case each mode that has to be excited requires one spatial light modulator which renders this approach relatively cost-intensive. Another approach is the so called spot based coupling where multiple Gaussian spots selectively address individual modes of the fm fiber [6,7]. A further common approach is based on evanescent field coupling. Here, selective matching of the propagation constants between the modes to be coupled is required, so that evanescent field coupling between these modes can take place [8]. The matching of the propagating constants can be realized by surface plasmons [9], bloch modes [10] or by matching of effective refractive indeces. The latter can be realized, for instance, by changing the coupler geometry, i.e., by applying asymmetric fiber cores [11] or by tapering and decreasing the core diameters [11,12]. However, this means that an individual geometry with small tolerances has to be produced for each coupling case between different modes which in turn makes this approach relatively cost-intensive as well. Moreover, the mode crosstalk of these approaches is quite high [13].

Micro-Structured and Specialty Optical Fibres V, edited by Kyriacos Kalli, Alexis Mendez,
Christian-Alexander Bunge, Proc. of SPIE Vol. 10681, 1068116 · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2306772

To overcome this complex manufacturing process a novel method for evanescent field based mode selective coupling between a sm fiber (SM1500, Fibercore) and a fm fiber (4 Mode fiber, OFS) was presented in [14] where the effective refractive indices of the modes to be coupled are matched by applying a fiber grating, as illustrated in Fig. 1.

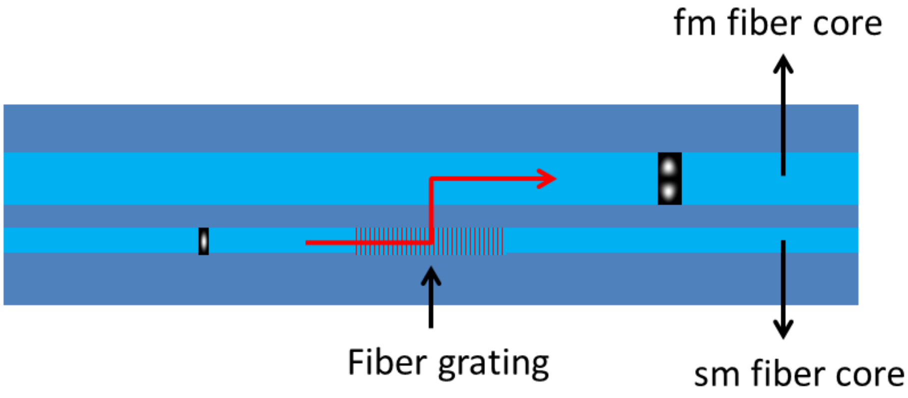

Figure 1: Principle of mode selective fiber coupling based on fiber gratings inscribed in the fiber core of the sm fiber.

The benefit of the grating assisted mode selective coupling concept is that the coupler geometry remains constant and only the grating period Λ has to be adapted for mode-selective coupling at a constant wavelength λ, as given in Equation (1).

$$\Lambda_M = \frac{\lambda}{|n_{eff,SM} - n_{eff,M}|} \tag{1}$$

Here, $n_{eff,SM}$ and n_{effM} are the effective refractive indeces of the sm and the fm fiber modes, respectively. Such a coupler can be manufactured by various manufacturing methods, e.g., by a fused-tapering process or by a grinding and polishing process. In this study, we present the first experimental results of the manufacturing process of a grating assisted asymmetric evanescent field polished coupler. Usually, for manufacturing of polished glass fiber couplers, the glass fibers are fixed in a curved groove incorporated in a quartz glass substrate. Then, the fixed fibers are grinded down together with the substrate until the top of the fiber core is uncovered [15]. This manufacturing procedure is not suitable for manufacturing of grating based evanescent field polished couplers because the cladding has to be removed evenly in the fiber grating section over the whole grating length of about 10 – 20 mm. In addition, an optical setup and method for adjustment and characterization of these coupling devices is required.

2. Manufacturing process

The manufacturing-process of asymmetric evanescent field polished couplers for grating assisted mode selective fiber coupling starts with inscribing of the fiber grating into the fiber core of the highly germanium doped single mode fiber SM1500 from Fibercore. Afterwards a grinding and polishing process is applied to the sm fiber and a 4 mode step index fm fiber from OFS. In a last step, the adjustment and fixing of the polished fibers takes place.

2.1 Fiber grating inscription

Simulations show that for mode selective coupling between the chosen sm and fm fiber in forward direction grating periods in the range of 100 µm are required. For inscribing fiber gratings with periods in this range, the methods commonly used for UV-induced inscription of long period fiber gratings based on amplitude masks or step-by-step techniques can be used. In this study, we fabricated UV-induced gratings by using an excimer laser and the amplitude mask technique in a well-established in house LPG-writing process. To enhance the photosensitivity of the sm fiber, it was hydrogen loaded (180 bar for 7 days) in a preceding step. The illumination setup is shown in Fig. 2. It should be noted that it is difficult to achieve fiber gratings with grating periods of 100 µm or less using the amplitude mask method because high pulse energy resistant amplitude masks with such small grating periods are difficult and expensive to realize. In this work a chrome mask is used which has the disadvantage that the energy of the UV light exposure is limited. Since the refractive index change Δn of the fiber core depends on the dose and hence on the energy of the UV light exposure relatively large grating lengths have to be applied in order to obtain sufficient coupling efficiencies.

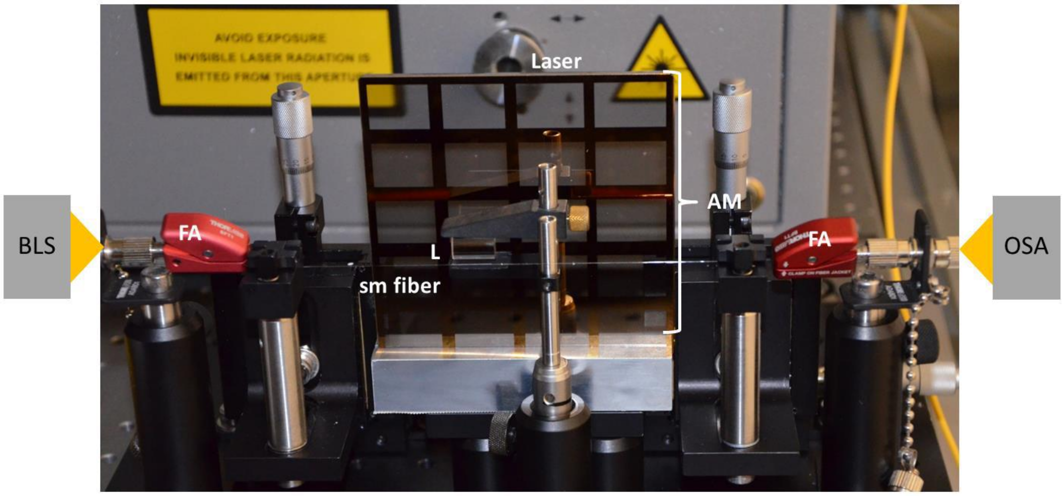

Figure 2: Set-up for inscribing of fiber gratings based on UV-illumination (KrF excimer laser) of a chrome amplitude mask (AM) and focusing of the grating pattern using a plan convex cylindrical lens (L). During illumination the fiber grating inscription is evaluated using a bright broadband light source (BLS) and an optical spectrum analyzer (OSA) connected to the sm fiber by fiber adapters (FA).

2.2 Coupler manufacturing

2.2.1 Preparing of the fibers

The manufacturing process starts with manufacturing of a special substrate for holding and fixing the fibers during both the polishing and characterization process. Four inch silicon (Si) wafers were applied as substrate material due to the higher hardness of Si compared to fused silica glass. The Si wafer will also acts as housing for the final coupler. In the first step, a 30 µm wide, 200 µm deep and 80 mm long groove was introduced into a Si wafer which acts as a reservoir (the transverse view of this groove is shown in Fig. 3 (a)) for the glue for fixing of the fibers. In the next step, a 150 µm wide and 50 µm deep (for the fm fiber) or a 150 µm wide and 59 µm deep (for the sm fiber) cut were axially overlaid with the first groove in the central polishing region. Inside this groove the fiber sections to be grinded and polished are placed, as shown in Fig. 3 (b). The parts of the fiber not to be grinded or polished are completely embedded inside the 150 µm deep groove in the Si wafer. As glue Crystalbond was chosen because glue surplus can be easily removed without residue by acetone. The polishing section is equal to the length of the LPG and this manufacturing step guarantees that the fiber cores of the sm and fm fibers are placed 2 µm below the wafer surface.

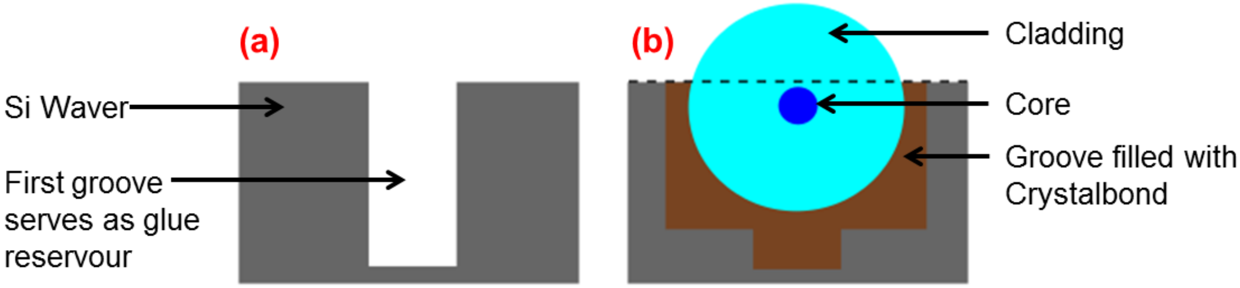

Figure 3: Transverse view of the Si wafer holder after introducing of the first groove which acts as glue reservoir (a) and fiber fixed in the final Si wafer holder with Crystalbond glue whereby the fiber core is placed close below the Si wafer surface.

Outside the polishing region, the first groove was overlaid with a groove 155 µm deep groove so that the fibers with 125 µm cladding diameter could be completely embedded in this structure.

2.2.2 Grinding and polishing process

The grinding of the fibers is realized by a disco grinding process using a DAC551 grinding machine. This machine enables high-precision work steps with a repeatability of 1 µm. A schematic representation of the grinding process is shown in Fig. 4.

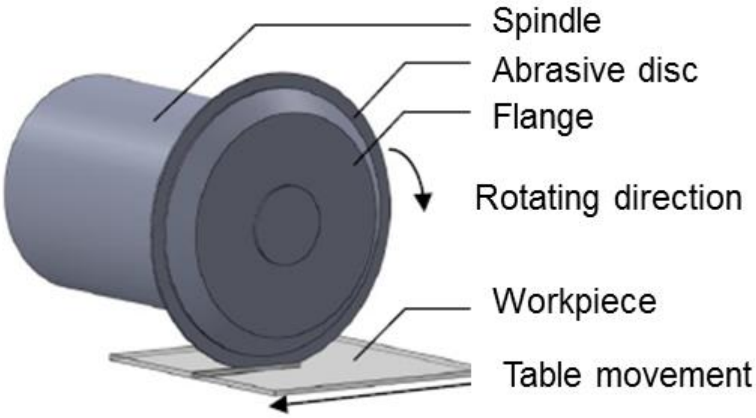

Figure 4: Principle of the disco grinding process.

The fiber cladding above the Si wafer surface is removed in one step by the rotating abrasive blade 20.000 revolutions / minute, a grinding blade diameter of 55 mm and a grain size of 45 µm. The latter was chosen because cutting of glass with smaller grain sizes leads to melting and smearing of the glass shavings whereby the molten glass residues then settle on the substrate and the fiber. The rotating abrasive blade is translated axially along the fiber whereas the Si wafer surface acts as stop due to the higher hardness of Si compared to fused silica. This guarantees that just enough cladding is removed in the process. After the grinding process, a chemical-mechanical polishing process is applied in order to achieve an optical surface quality. During this process, the Si wafer with the grinded fibers is attached to a chuck by means of an adhesive foil. The whole arrangement is then placed on the polishing cloth. The polishing cloth and the chuck have an opposite direction of rotation in order to generate friction. To facilitate ablation, slurry between the polishing cloth and the chuck was added and a slurry film forms as illustrated in Fig. 5.

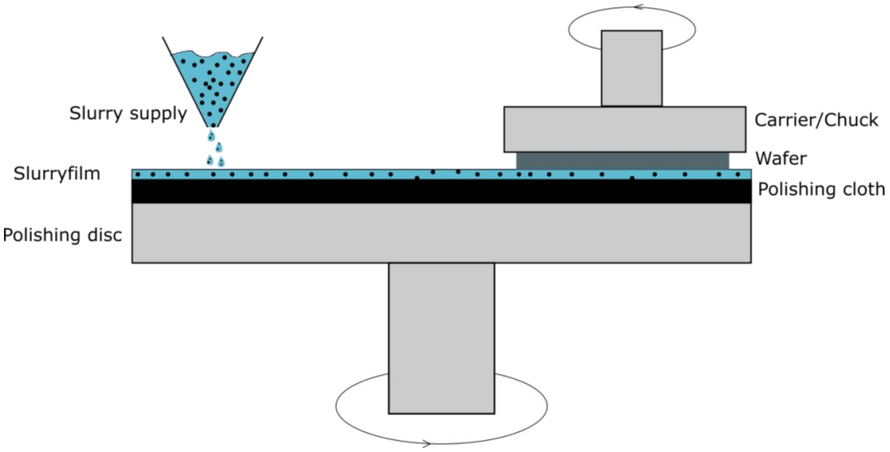

Figure 5: Principle of the polishing process, whereby the Si wafer with the grinded fibers is fixed in the chuck by an adhesive foil.

In the process, slurry was added at certain intervals to avoid excessive dry friction between the polishing cloth and the wafer. The particles contained in the slurry lead to sufficient polishing of the glass fiber. This procedure is carried out for one hour and examined at defined intervals.

3. Results of the optical surface quality

An electron microscope image obtained after applying the grinding process to the fiber is shown in Fig. 6.

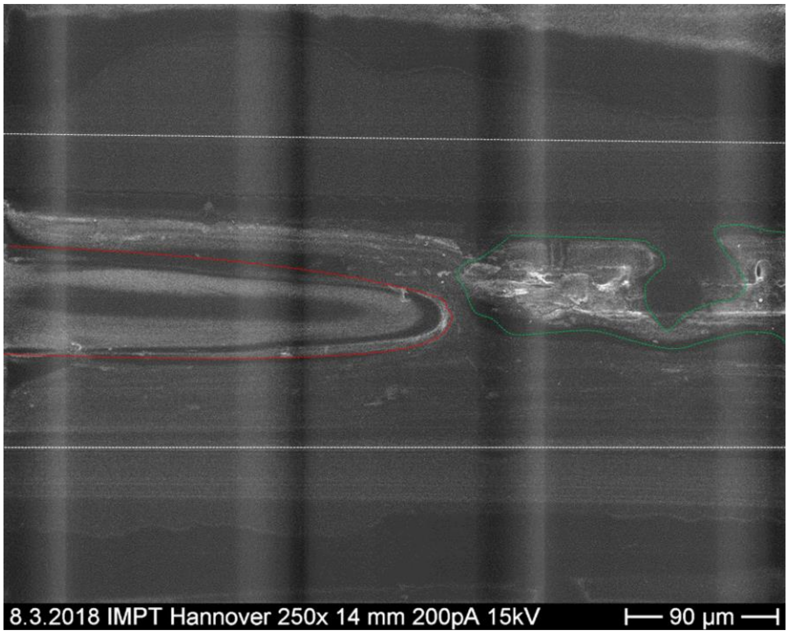

Figure 6: Scanning electron microscope image obtained after applying the disco grinding process to the fm fiber which is placed in the groove illustrated by the white dashed lines. The transition from the grinded section (inside the red dashed lines) to the unprocessed fiber is clearly visible. The area inside the green dashed line contains glue (Crystalbond).

In order to measure the surface roughness of the fibers, a nanoindenter (Hysitron TI 900 triboindenter) was used. There, a surface scan (20 x 20 µm) was performed using the scanning force microscope mode whereby a force of 3 µN was applied by the measuring tip (Berkovich diamond tip) to the polished glass fiber surface. Three measurements were taken at 3 different locations of the fiber to avoid measurement uncertainties. Fig. 7 shows the surface scan of the fiber. The evaluation of the surface scan resulted in surface roughness $R_a = 2.2 \pm 1.2$ nm.

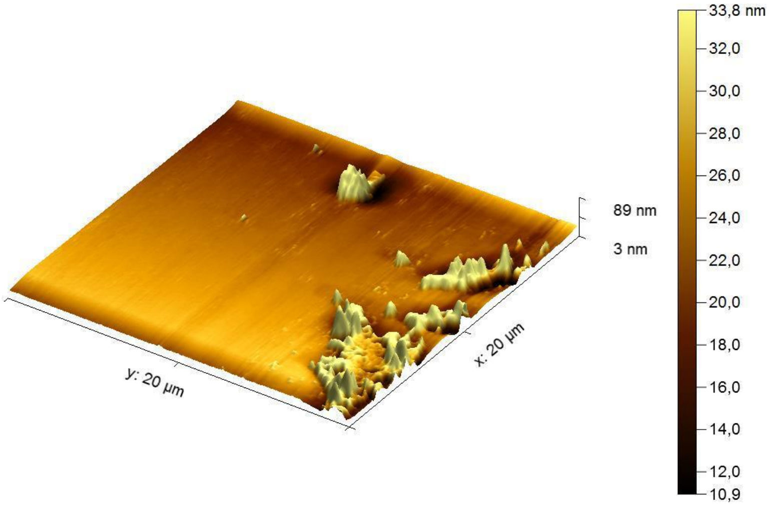

Figure 7: Result of the tactile surface measurement of a 20 x 20 µm sector of the polished area of the fiber using a Hysotron as measurement device. An optical surface quality with roughness $R_a = 2.2 \pm 1.2$ nm was measured. The larger elevations in the right area of the scan result from dust particles.

4. Characterization of the manufactured couplers

The characterization of the mode selective couplers comprises the spectral behavior, the polarization sensitivity, the mode-dependent attenuation, the mode selectivity, and the mode crosstalk.

4.1 Characterization setup

For optical characterization of the couplers the optical setup shown in Fig. 8 was developed.

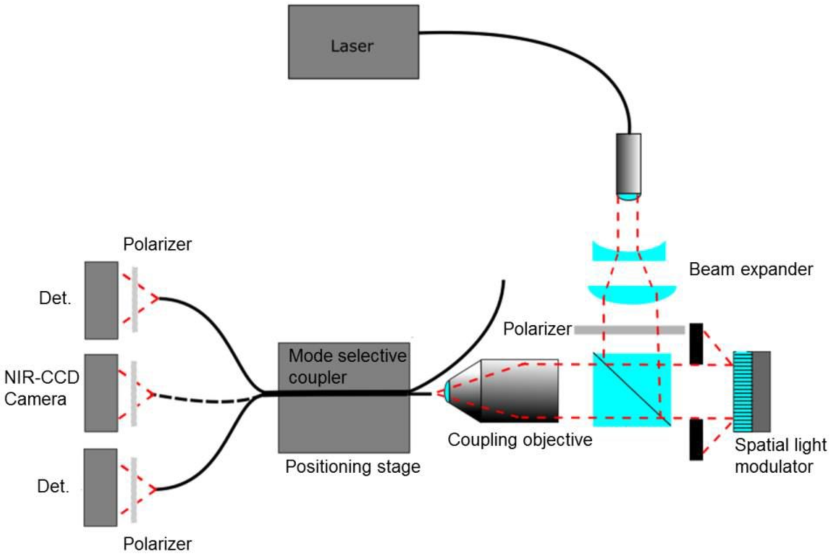

Figure 8: Characterization setup employed for selective excitation of the fm fiber modes using a spatial light modulator (SLM).

A wavelength and power tunable laser (New Focus, Tunable Laser TLB-6600) is used as light source. The laser beam diameter is extended and collimated before the laser beam is binary phase modulated by a liquid crystal spatial light modulator (SLM) (Holoeye, PLUTO TELCO -013 Phase Only Modulator). This allows the digital excitation of various modes by the phase mask technique [4,5], as illustrated in Fig. 9. Then, the digitally excited mode field is coupled into the fm fiber core input of the mode selective fiber coupler. At the fm fiber and sm fiber outputs of the coupler, the transmitted power levels are detected by photodiodes, with polarizers placed in front of them, and evaluated by a LabView code. Also a NIR CCD camera (Point Grey, CMLN-13S2M-CS) with a polarizer is integrated into the setup and the fm fiber output can be switched between the photodiode detector and the NIR-CCD camera. In addition to the fm fiber input, the sm fiber input can also be used as power input by directly connecting the sm fiber to the tunable laser source. The polished fiber coupler is placed on a positioning stage (Thorlabs, S148C) which enables the alignment of the polished fibers with respect to each other using four degrees of freedom.

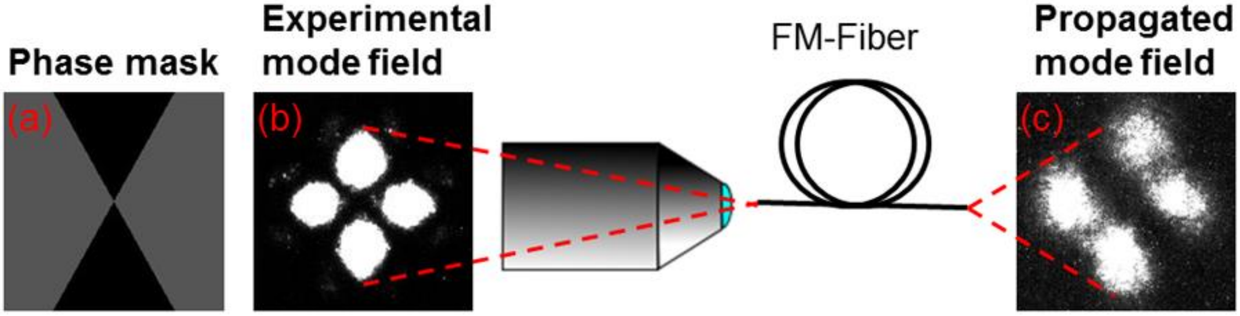

Figure 9: The phase mask in (a) is used to excite the LP_{21} mode field (b) in the above characterization setup. The measured mode field obtained by the NIR CCD camera after mode propagating through the fm fiber core is shown in (c).

4.2 Characterization Methods

For characterization of the mode selectivity of the coupler, the sm fiber input can be used as power input and the mode field at the fm fiber output of the coupler can be detected by the NIR CCD camera and evaluated visually. For measurement of the mode dependent attenuation, the fm fiber input can be used as power input whereby the mode to be coupled is excited by the SLM. The fm and sm fiber outputs are connected to the detectors 1 and 2, respectively.

Based on the measured power values, the mode-dependent attenuation can be calculated from the relative proportion of the radiation coupled from the fm fiber mode into the sm fiber. In order to minimize the mode-depended attenuation, in case of coupling of a non-circular mode field (e.g. LP_{11} or LP_{21}), the latter can be rotated by the SLM. This enables to determine the best spatial orientation for coupling. The crosstalk to other modes which should not to be coupled into the fm fiber can be measured similarly to the mode-dependent attenuation. For mode crosstalk evaluation, all modes which should not to be coupled are excited and the relative power transfer of these modes from the fm fiber to the sm fiber is to be calculated. To evaluate the spectral behavior of the coupler, the mode selectivity and mode-dependent attenuation as well as the mode crosstalk can be evaluated in a spectral range from 1510 nm to 1620 nm by using the wavelength sweep-mode of the laser system. Finally, the polarization dependence can be evaluated by controlling the polarization at the input of the coupler and analyzing the state of polarization by the analyzers placed between the coupler outputs and the detectors, respectively.

5. Conclusion

The grating assisted evanescent field coupling approach for mode selective coupling presented here can lead to a technological progress in the field of MDM since it allows mode selective coupling without the necessity of different coupler geometries for coupling of different modes. It also allows more flexibility in the manufacturing and design of the coupler with respect to different manufacturing processes and geometries. The approach discussed could reduce the manufacturing costs and increase the longterm stability of the coupler structures. The novel manufacturing process for asymmetric glass fiber couplers allows a precise and even removal of the fiber cladding and leads to optical surface quality over the length of the fiber grating. The developed process can also be used for the production of symmetric evanescent field optical fiber couplers. Furthermore, the process can be beneficial for the development of glass fiber based sensors where the fiber core is exposed to environmental influences and effects.

In addition to the coupling approach, a optical setup for characterization and optimization of mode selective polished fiber couplers is presented. A similar setup could also be used for MDM based data transmission in a future step.

Acknowledgement

The authors acknowledge support of the Deutsche Forschungsgemeinschaft (DFG) within Grant Number OV 36/31-1.

References

[1] D.J. Richardson, J.M. Fini, L.E. Nelson. Space-division multiplexing in optical fibers. Nature Photonics, vol. 7, 354-362. (2013).

[2] H. Takara, A. Sano, H.Kubota, et al., European Conference and Exhibition on Optical Communication, Postdeadline Session III. Amsterdam, Netherlands. 1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency (2012).

[3] R. Ryf, N.K. Fontaine, M.A. Mestre, et al., Frontiers in Optics, FiOPostdeadline Session III. New York, United States. 12 x 12 MIMO Transmission over 130-km Few-Mode Fiber (2012).

[4] B. Franz, H. Bülow. Experimental Evaluation of Principal Mode Groups as High-Speed Transmission Channels in Spatial Multiplex Systems. IEEE Photonics Technology Letters, vol. 24., S. 1363-1365 (2012).

[5] B. Franz, H. Bülow. Mode Group Division Multiplexing in Graded-Index Multimode Fiber. Bell Labs Technical Journal 18(3), 153-172, (2013).

[6] R. Ryf, S. Randel, A.H. Gnauck. Mode-Division Multiplexing Over 96 km of Few-Mode Fiber Using Coherent 6x6 MIMO Processing. Journal of Lightwave Technology, vol. 30., 521-531 (2012).

[7] R. Ryf, M.A. Mestre, S. Randel. Mode-Mulitplexed Transmission Over a 209km DGD-Compensated Hybrid Few-Mode Fiber Span. IEEE Photoincs Technology Letters, vol. 24., 1965-1968 (2012).

[8] M.S. Whalen, T.H. Wood. Effectively Nonreciprocal Evanescent-Wave Optical Fibre Directional Coupler. Electronics Letters, vol. 21, 175-176 (1985).

[9] S. Barcelos, M.N. Zervas, P. St J. Russell. Selective Excitation of Fiber-Modes Using Surface Plasmons. IEEE Photonics Technology Letters, vol. 7, 1051-1053 (1995).

[10] R.D. Pechstedt, P. St J. Russell, T.A. Birks, F.D. Lloyd-Lucas. Selective coupling of fiber modes with use of surface-guided Bloch modes supported by dielectric multilayer stacks. Journal of the Optical Society of America A, vol. 12, 2655-2659 (1995).
[11] K.Y. Song, I.K. Hwang, S.H. Yun. High Performance Fused-Type Mode-Selective Coupler Using Elliptical Core Two-Mode Fiber at 1550nm. IEEE Photonics Technology Letter, vol. 14, 501-503 (2012).
[12] N. Riesen, J.D. Love. Weakly-Guiding Mode-Selective Fiber Coupler. IEEE Journal of Quantum Electronics, vol. 48, 941-945 (2012).
[13] S. Barcelos, M. N. Zervas, P.St J. Russell. Selective excitation of fiber-modes using surface plasmons. IEEE Photonics Technol. Lett. 7, 1051-1053 (1995).
[14] K. Bremer, S. Lochmann, B. Roth. Grating assisted optical waveguide coupler to excite individual modes of a multi-mode waveguide. Optics Communications 356, 560-564 (2015).
[15] R.P. Dahlgren, R.E. Sutherland. Polished coupler and resonator fabrication. SPIE, Fiber Optic and Laser Sensors X, Vol. 1795, 60-68 (1992).