Experimental realization of transverse mode conversion using optically induced transient long-period gratings

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In optical communication technology spatial-division multiplexing has gained a lot of attention due to an expected capacity crunch in common communication schemes [1]. One possibility to further scale data capacities is utilizing transverse modes of few-mode fibers as multiplicator for having access to additional channels [2]. One challenging aspect within these new technologies lies in optical routing and switching the newly acquired channels, where spatial channel switching today still relies on microelectromechanical optical switching [3].

Now, we are able to present the experimental realization of optically induced transverse mode conversion in a few mode fiber via an optically induced, localized, traveling, long-period grating. Accompanying numerical simulations are a helpful tool for better understanding the involved effects and show excellent agreement to the experimental results.

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1. Introduction

Optical fibers with large core diameter generally allow the propagation of several transverse eigenmodes of the electric field. While these modes propagate independently in undisturbed straight fibers, any inhomogeneity leads to their coupling, and periodic perturbations of the fiber can result in effective energy transfer between the modes [4]. This long-period grating structure inside the fiber is usually permanently written using UV [5] or pulsed radiation [6] or exploiting inherent photosensitivity in Germanium-doped fibers [7]. However, transiently written gratings optically induced by counterpropagating high-power nanosecond pulses via the Kerr-effect (OLPG, optically induced long-period gratings) have recently been presented and used for transverse mode conversion [8]. Since the latter can be switched on and off, they offer applicability for optical switching, although the pulse energies used for these quasi-continuous-wave experiments were in the order of the damage threshold of the fiber facets.

In this paper, we present the necessary steps in pushing OLGPs towards potential applications in telecommunications. In order to reduce the required pulse energies to a feasible level only part of the grating can be written at any time, implying that the grating has to travel alongside the signal that is to be switched into a different mode. The use of co-propagating femtosecond pulses for the creation of an OLPg and the conversion of transverse fiber modes presented here, thereby reduces the required pulse energy by almost three orders of magnitude compared to [8]. By coupling a write beam into a mixture of two transverse modes (LP01 and LP02) of an optical few-mode fiber, the differing propagation constants of the modes lead to multimode interference (MMI) along the fiber, creating a periodic spatio-temporal intensity pattern due to the shape of the modes (see Fig. 1a). As the Kerr-effect connects the refractive index to the local intensity, this results in a long-period phase grating, with the grating constant being defined by the difference of the propagation constants of the write modes [9]. For the experiments a co-propagating and orthogonally polarized femtosecond probe beam at the same wavelength was coupled into the fundamental mode of the fiber. As the propagation constant of that probe beam then differed from the one of the LP02-mode by exactly the grating constant, the phase-matching condition [10] was inherently fulfilled. Thus, the probe beam was diffracted at the OLPg and partially converted into the LP02-mode.

2. Experimental Setup

The experimental setup is shown in detail in Fig. 1b. The diameter of the write beam was chosen to be smaller than that of the fundamental fiber mode in order to excite a mixture of the LP01- and the LP02-mode. The probe beam was mode-matched to the LP01-mode of the fiber as good as possible, but care was taken to maximize the temporal overlap of write and probe pulses. As the discrimination of probe and write beam is based on po-
Fig. 1. Schematic diagram of the experimental setup (angles and distances are not drawn to scale). Pump and probe beam for the experiment were provided by an amplified, mode-locked Ytterbium fiber laser delivering ultrashort pulses with a duration of approximately 400 fs at a repetition frequency of 1 MHz and a center wavelength of about 1033 nm. The probe beam path also included a piezo-driven delay stage (Δt) for adjusting the temporal overlap between pump and probe pulses. After recombining the cross-polarized write and probe beams with a polarizing beam splitter (PBS1) both were coupled into a few-mode fiber (nLIGHT Passive 25, 6.5 cm fiber length). PD1-PD3: photodiodes, WDG: wedged glass substrate, L1-L3: lenses, MMF: multi-mode fiber, MO: microscope objective, HWP: half-wave plate, Pol: polarizer, CCD: charged-coupled device camera, PH: pinhole.

Fig. 2. Measured normalized excited modal contents (orientational degeneracy marked with “e”) in the Passive 25 fiber for the write and probe beam individually.

The modal contents were measured with a modified version of the correlation filter presented by Flamm et al. [11]: The fiber end-facet was magnified by a 100x microscope objective, the beam of interest was filtered by means of a half-wave plate and a polarizing beam splitter and then relay imaged to a phase-only spatial light modulator (SLM). By applying pre-calculated phase patterns specific to each mode a power proportional to the modal weight was diffracted into the center of the first diffraction order in the far field [11]. In comparison to Flamm et al. [11] we modified the measurement technique by replacing the evaluation of a single CCD camera pixel with a fast photodiode (PD) and by placing a pinhole with a diameter of 10 µm accurately in front of the PD. We then determined the position of the pinhole in the Fourier plane by applying a phase grating to the SLM and scanning its period. This modification allowed us to measure the individual modal contents with up to 12 kHz, only limited by the measurement bandwidth of the applied PD and thereby to resolve the modal contents in dependence of the relative phase between probe and write beam. The feasibility of the modal reconstruction with the acquired values from the PD was verified by a separate measurement utilizing a CCD camera. Figure 2 shows the measured normalized modal contents of both beams individually, when the transmission of the beam under test at PBS2 was maximized using the half-wave plate and the other beam was blocked. The write beam had an almost equal distribution between the fundamental mode and the LP$_{02}$-mode with only marginal power in other higher-order transverse modes and it was verified that its modal content did not change during the course of the measurements. The maximum amount of energy of the probe beam was measured to be in the fundamental mode.

In order to measure mode conversion in the probe beam, the write beam was suppressed by minimizing its transmission at the PBS2. The contrast at PBS2 was good enough (about 100:1) so that linear interference between the transmitted rest of the write beam and the probe beam was negligible when the probe beam was set to 10% of the write beam’s power throughout the experiment. However, at the peak powers necessary for inducing a long period grating via the Kerr effect, the aforementioned nonlinear polarization rotation (NPR) occurred. In fact, NPR rotates the polarization ellipse of the input light field by an angle θ ∝ sin(Δφ), where Δφ is the phase difference between the cross-polarized probe and write beam, effectively leading to a cross-talk between both beams and possibly disturbing the...
Fig. 3. a) Probe power measured with PD2 in dependence of the phase difference between probe and write beam in front of the fiber at an average write beam power of 150 mW and an average probe beam power of 15 mW. The horizontal dashed line indicates the probe power \( P_0 \) without a write beam present. The markers indicate phase delays that are investigated in more detail in sub-figure b: here, the write power dependent difference between the probe power levels “with” and “without” write beam present is depicted for different phase differences measured with PD1 (dotted lines to guide the eye). For details see the text.

measurement: Due to unavoidable mechanical fluctuations in the setup, this phase difference varied over time and furthermore, even small contributions to the phase difference between both beams caused by residual fiber birefringence led to strong NPR. In order to be able to account for or even avoid this unwanted, obstructing cross-talk and thereby to be able to measure mode conversion, we studied the occurring NPR in dependence of the phase difference: We measured the transmission of the probe beam’s power through PBS2 behind the fiber (with PD2) while ramping the delay of the probe beam with a sub-Hz frequency and measuring the phase difference to the write beam in front of the fiber with PD1. The result is depicted in Fig. 3a for a write pulse energy of 150 nJ. The measurement shows a \( \pi \)-periodicity as it is expected from NPR. The polarization ellipse formed by the interference of write and probe beam is periodically rotated into and out of the probe beam’s polarization direction. The average probe power \( P_0 \) measured with a blocked write beam is therefore periodically exceeded and undershot. However, note that NPR only occurs for elliptically polarized light so that no NPR would have been expected at a phase difference of zero or \( \pi \) in front of the fiber. The large difference in measured probe power from \( P_0 \) at these phase difference values can only be attributed to a phase shift due to residual birefringence in the fiber and shows that it cannot be neglected in the case of NPR. To identify the optimal input phase difference \( \phi_0 \) for minimal cross-talk between both beams we measured the phase-dependent average probe output power for write input powers equal to pulse energies ranging from 10 nJ to 250 nJ. We then calculated for each phase difference the sum of the root mean square deviations from the unaltered probe power values \( P_0 \) measured with a blocked write beam. The phase difference with the minimum root mean square deviation from the unaltered probe powers is identified as \( \phi_0 \) in Fig. 3a. The deviation from \( P_0 \) in dependence of write beam power for \( \Delta \phi = \phi_0 \) is shown in detail in Fig. 3b. Furthermore, the power difference is depicted for \( \phi_0 + 0.18 \pi \) as well as for \( \phi_0 - 0.04 \pi \) to demonstrate the nonlinear transfer of write power into the probe beam as well as of probe power into the write beam. The former effect appears much stronger as the write beam holds ten times the power of the probe beam.

3. Mode conversion

We then measured the LP\(_{01} \) as well as LP\(_{02} \)-modal content in the probe beam in dependence of the write beam’s power and thereby in dependence of the degree of index modulation of the OLPG. For each write beam power the modal contents were measured in dependence of the phase difference between both beams using photodiode PD3. The measurement was then evaluated at the optimal phase difference for minimal NPR, and the resulting normalized evolution of the LP\(_{01} \) as well as LP\(_{02} \)-modal content is shown in Fig. 4. The black squares and diamonds depict the modal content of the probe modes when the write beam was blocked and therefore no OLPG was present. The relative modal contents were constant within the measurement error. The same was found to hold true for an unblocked but delayed write beam. In this case, although an OLPG was transiently written, the instantaneous nature of the Kerr-effect led to no conversion if the probe pulses did not overlap in time with the written grating. These tests verified that no temperature-induced contribution on writing the OLPG was present in our setup. The red triangles in Fig. 4 finally show the evolution of the fundamental LP\(_{01} \)-mode when the probe pulse overlapped in time with the OLPG while the blue triangles depict the evolution of the higher-order LP\(_{02} \)-mode in dependence of the write pulse energy. A conversion of probe energy from the LP\(_{01} \) to the LP\(_{02} \)-mode could be observed, reaching its maximum conversion with a relative LP\(_{02} \)/LP\(_{01} \)-mode content of 46% at a write beam average power equivalent to a pulse energy of 120 nJ. For even higher write beam pulse energies back-conversion occurred until the probe energy in the LP\(_{02} \)-mode reached a local minimum at about 230 nJ write pulse energy.

In order to get a better understanding why the experimentally observed mode-conversion did not surpass 50% conversion efficiency as it has been already demonstrated in a numerical study [9] the involved ultrashort pulses were studied in more detail. And indeed, the intensity auto-correlation of the pulses in use here revealed significant energy in a structure surrounding the 400 fs pulse up to delays of about 5 ps. This pedestal effects the measured mode conversion in a twofold man-
ner: Not only is the peak power considerably reduced compared to bandwidth limited pulses, but also does the energy in the picosecond pedestal not take part in the nonlinear conversion process. However, the unaltered modal distribution of these temporal parts of the probe beam was still included in the measured modal power and thereby constitutes an offset in the relative modal content, reducing the maximum theoretically possible conversion efficiency. Therefore, we performed numerical simulations based on coupled nonlinear Schrödinger type equations (see [9] for details on the simulations) specifically for the scenario studied here (dashed-dotted red and dashed blue curve in Fig. 4). To account for the effective loss in peak power for mode conversion we assumed bandwidth-limited 400 fs pulses but with reduced pulse energy. The linear offset in the final modal content was considered by adding the missing pulse energy after the simulation but with the initial, unaltered modal distribution. With these simple assumptions we observed very good agreement with the experimentally observed mode conversion when assuming 35% of the pulse energy to be in the picosecond pedestal (see Fig. 4). To get rid of the remaining small residual deviations between simulation and experiment it would be required to fully characterize phase and amplitude of the laser pulses and perform numerical simulations considering the full temporal pulse structure.

4. Conclusion

In conclusion, we have shown for the first time the mode conversion in a fiber from the fundamental mode to the LP$_{02}$-mode by use of an optically induced long-period grating that travels along the fiber. This grating could be switched on and off since it was transiently writ-ten using the Kerr-effect, and relatively low pulse energies of 120 nJ in the write beam were sufficient due to the use of femtosecond pulses. By adapting this new scheme the required pulse energies could already be reduced by almost three orders of magnitude (about a factor of 600) compared to preceding quasi-continuous-wave experiments. However, the necessary pulse energies need to be further reduced into the pJ-regime for this scheme to be applicable in future integrated optical communication systems. The according progress is expected to be achieved by the use of highly nonlinear waveguides, e.g. fibers made of chalcogenide glass or integrated waveguides made of silicon exhibiting an increased nonlinearity by a factor of 100 up to 50000 [12, 13]. Furthermore, numerical simulations of multimode coupled nonlinear Schrödinger equations proved to be a helpful tool for understanding the involved mechanisms and showed excellent agreement with the experimentally measured mode-conversion. Numerical simulations will therefore continued to be used for identification of the best suited nonlinear platform for all-optical mode switching. For future experiments, we plan to fully eliminate the possible cross-talk of write and probe beam originating from nonlinear polarization rotation by exploiting a dichroic setup that we already numerically studied elsewhere [14, 15].

References

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson, Nature Photonics 7, 354 (2013).
[2] J. Carpenter, B. C. Thomsen, and T. D. Wilkinson, Journal of Lightwave Technology 30, 3946 (2012).
[3] N. Amaya, M. Irfan, G. Zervas, R. Nejabati, D. Siméonidou, J. Sakaguchi, B. J. Puttnam, T. Miyazawa, Y. Awaji, N. Wada, and I. Heming, Optics Express 21, 8865 (2013).
[4] K. Hill, B. Malo, K. Vineberg, F. Bilodeau, D. Johnson, and I. Skinner, Electronics Letters 26, 1270 (1990).
[5] A. Vengsarkar, P. Lemaire, J. Judkins, V. Bhatia, T. Erdogan, and J. Sipe, Journal of Lightwave Technology 14, 58 (1996).
[6] Y. Kondo, K. Nouchi, T. Mitsuyu, M. Watanabe, P. G. Kazansky, and K. Hirao, Optics Letters 24, 646 (1999).
[7] H. Park and B. Kim, Electronics Letters 25, 797 (1989).
[8] N. Andermahr and C. Fallnich, Optics Express 18, 4411 (2010).
[9] T. Walbaum and C. Fallnich, Applied Physics B 103, 10.1007/s00340-013-5593-0.
[10] J. Bures, Guided Optics (Wiley/VCH, New York, 2009).
[11] D. Flamm, D. Naidoo, C. Schulze, A. Forbes, and M. Duparré, Optics Letters 37, 2478 (2012).
[12] B. J. Eggleton, B. Luther-Davies, and K. Richardson, Nature Photonics 5, 141 (2011).
[13] Y. Ding, J. Xu, H. Ou, and C. Peucheret, Optics Express 22, 127 (2014).
[14] M. Schäferling, N. Andermahr, and C. Fallnich, Applied Physics B 102, 809 (2011).
[15] T. Hellwig, T. Walbaum, and C. Fallnich, Applied Physics B 112, 499 (2013).
References

[1] Richardson, D. J., Fini, J. M. & Nelson, L. E. Space-division multiplexing in optical fibres. *Nature Photonics* 7, 354–362 (2013). URL http://dx.doi.org/10.1038/nphoton.2013.94 http://www.nature.com/doifinder/10.1038/nphoton.2013.94.

[2] Carpenter, J., Thomsen, B. C. & Wilkinson, T. D. Degenerate Mode-Group Division Multiplexing. *Journal of Lightwave Technology* 30, 3946–3952 (2012). URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6227317.

[3] Amaya, N. et al. Fully-elastic multi-granular network with space / frequency / time switching using multi-core fibres and programmable optical nodes. *Optics Express* 21, 8865–8872 (2013).

[4] Hill, K. et al. Efficient mode conversion in telecommunication fibre using externally written gratings. *Electronics Letters* 26, 1270 (1990). URL http://digital-library.theiet.org/content/journals/10.1049/el_19900818.

[5] Vengsarkar, A. et al. Long-period fiber gratings as band-rejection filters. *Journal of Lightwave Technology* 14, 58–65 (1996). URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=476137.

[6] Kondo, Y. et al. Fabrication of long-period fiber gratings by focused irradiation of infrared femtosecond laser pulses. *Optics Letters* 24, 646 (1999). URL http://www.opticsinfobase.org/abstract.cfm?URI=ol-24-10-646 http://www.ncbi.nlm.nih.gov/pubmed/18073810.

[7] Park, H. & Kim, B. Intermodal coupler using permanently photoinduced grating in two-mode optical fibre. *Electronics Letters* 25, 797 (1989). URL http://digital-library.theiet.org/content/journals/10.1049/el:19890538.

[8] Andermahr, N. & Fallnich, C. Optically induced long-period fiber gratings for guided mode conversion in few-mode fibers. *Optics Express* 18, 4411 (2010). URL http://www.opticsinfobase.org/abstract.cfm?URI=oe-18-5-4411.

[9] Walbaum, T. & Fallnich, C. Theoretical analysis of transverse mode conversion using transient long-period gratings induced by ultrashort pulses in optical fibers. *Applied Physics B* (2013). URL http://link.springer.com/10.1007/s00340-013-5593-0.

[10] Bures, J. *Guided Optics* (Wiley/VCH, New York, 2009).

[11] Flamm, D., Naidoo, D., Schulze, C., Forbes, A. & Duparré, M. Mode analysis with a spatial light modulator as a correlation filter. *Optics Letters* 37, 2478 (2012). URL http://www.ncbi.nlm.nih.gov/pubmed/22743427 http://www.opticsinfobase.org/abstract.cfm?URI=ol-37-13-2478.

[12] Eggleton, B. J., Luther-Davies, B. & Richardson, K. Chalcogenide photonics. *Nature Photonics* 5, 141–148 (2011). URL http://www.nature.com/doifinder/10.1038/nphoton.2011.309.

[13] Ding, Y., Xu, J., Ou, H. & Peucheret, C. Mode-selective wavelength conversion based on four-wave mixing in a multimode silicon waveguide. *Optics Express* 22, 127–35 (2014). URL http://www.ncbi.nlm.nih.gov/pubmed/24514974.

[14] Schäferling, M., Andermahr, N. & Fallnich, C. Investigations on the wavelength dependence of optically induced long-period Bragg gratings. *Applied Physics B* 102, 809–817 (2011). URL http://www.springerlink.com/index/10.1007/s00340-011-4395-5.

[15] Hellwig, T., Walbaum, T. & Fallnich, C. Optically induced mode conversion in graded-index fibers using ultra-short laser pulses. *Applied Physics B* 112, 499–505 (2013). URL http://link.springer.com/10.1007/s00340-013-5645-8.