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*Published in:*  
Scientific Reports

*Link to article, DOI:*  
[10.1038/srep34693](https://doi.org/10.1038/srep34693)

*Publication date:*  
2016

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Christensen, E. N., Koefoed, J. G., Friis, S. M. M., Usuga Castaneda, M. A., & Rottwitt, K. (2016). Experimental characterization of Raman overlaps between mode-groups. *Scientific Reports*, 6, [34693]. DOI: 10.1038/srep34693

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# SCIENTIFIC REPORTS



OPEN

## Experimental characterization of Raman overlaps between mode-groups

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Received: 10 June 2016  
Accepted: 19 September 2016  
Published: 05 October 2016

Mode-division multiplexing has the potential to further increase data transmission capacity through optical fibers. In addition, distributed Raman amplification is a promising candidate for multi-mode signal amplification due to its desirable noise properties and the possibility of mode-equalized gain. In this paper, we present an experimental characterization of the intermodal Raman intensity overlaps of a few-mode fiber using backward-pumped Raman amplification. By varying the input pump power and the degree of higher order mode-excitation for the pump and the signal in a 10 km long two-mode fiber, we are able to characterize all intermodal Raman intensity overlaps. Using these results, we perform a Raman amplification measurement and demonstrate a mode-differential gain of only 0.25 dB per 10 dB overall gain. This is, to the best of our knowledge, the lowest mode differential gain achieved for amplification of mode division multiplexed signals in a single fiber.

During the past decade, the increase in data capacity per fiber has slowed relative to the rapid progress in the 1990's while, at the same time, the demand for capacity continues to grow exponentially<sup>1</sup>. Current methods for signal multiplexing, i.e. wavelength-, polarization-, time-, and quadrature-division multiplexing, are approaching their fundamental limits so new means of multiplexing are needed. Space-division multiplexing<sup>2</sup> in the form of multi-core fibers has already been used to achieve new heights in data capacity from a single laser source<sup>3,4</sup>; in single-core fibers supporting multiple spatial modes, long-distance propagation of optical signals has been demonstrated<sup>5,6</sup>; and recently, data transmission in a few-mode multi-core fiber was presented<sup>7</sup>. One important challenge of mode-division multiplexing (MDM) systems is building multi-mode optical amplifiers, that have mode-equalized amplification of all spatial modes, to compensate for example for distributed fiber loss; it is desirable for a multi-mode amplifier to avoid mode-dependent gain (MDG) in order to maximize capacity<sup>8</sup>. As for traditional single-mode systems, discrete Erbium-doped fiber amplifiers have been applied to multi-mode systems as well and low MDG has been achieved for some of the modes in fibers with specially designed Erbium-doping profiles<sup>9–11</sup>.

Another approach to counter-balance fiber losses is distributed Raman amplification, which is also widely used already in single-mode networks due to its superior noise properties in the backward-pumped configuration<sup>12</sup>. Furthermore, it has been shown theoretically that minimal MDG is possible by coupling pump power into a specific combination of spatial modes<sup>13</sup>, or by optimizing fiber design<sup>14</sup>, which makes Raman amplifiers a promising candidate for realizing low-loss, multi-mode transmission links over large distances.

Earlier work has demonstrated Raman gain between higher-order modes with the pump in only one mode<sup>5,15,16</sup>. Besides the obvious challenges related to exciting the pump in a specific combination of modes, it may often also prove difficult to determine the exact mode combination that leads to the lowest possible MDG because the required fiber data are unavailable from the fiber supplier. In this paper, we present an experimental characterization of the intermodal Raman intensity overlap of the guided modes of a two-moded (6 modes counting polarisation and LP<sub>11a</sub> and LP<sub>11b</sub>) few-mode fiber (FMF) using mechanically induced long-period gratings (LPGs) to excite the higher-order modes. Using the obtained results, we demonstrate backward pumped Raman amplification of a continuous wave (CW) signal through 10 km of a two-moded fiber with a very low MDG of 0.25 dB per 10 dB gain by pumping in a combination of the LP<sub>01</sub> and LP<sub>11</sub> modes. The mode-differential gain obtained required no prior knowledge about the Raman intensity overlaps of the fiber.

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## Results

The purpose of the present work is to characterize the intermodal Raman overlaps and use them to achieve a minimal MDG in a backward-pumped Raman fiber amplifier. This is done by coupling the pump light into the fiber in the correct combination of the LP<sub>01</sub>- and LP<sub>11</sub>-modes. As will be discussed in the Methods section below, due to strong mode-coupling, the two-fold quasi-degenerate LP<sub>01</sub>-modes and four-fold quasi-degenerate LP<sub>11</sub>-modes are simply considered as two distinct groups of modes. We carry out two measurements: Firstly, the Raman gain of a continuous wave signal in the LP<sub>01</sub>-mode is measured vs. total pump input power for five different modal compositions of the pump, i.e. different combinations of the LP<sub>01</sub>- and the LP<sub>11</sub>-modes. Secondly, both pump and signal are converted to LP<sub>11</sub>. This data is used to calculate the Raman intensity overlaps relative to the LP<sub>01</sub>-LP<sub>01</sub>-overlap, which is all that is needed to find the correct combination of pump modes.

**Raman intensity modal overlaps.** Assuming both pump, and signal to be CW sources, the signal power  $P_i^s$ , in spatial mode  $i$ , and the counter propagating  $P_j^{p,-}$  and copropagating pump power  $P_j^{p,+}$ , in spatial mode  $j$ , is governed by<sup>17</sup>

$$\frac{dP_i^s}{dz} = -\alpha_s P_i^s + \gamma_R \left( \sum_j F_{i,j} (P_j^{p,+} + P_j^{p,-}) \right) P_i^s, \quad (1)$$

$$\frac{dP_j^{p,\pm}}{dz} = \mp \alpha_p P_j^{p,\pm} \mp \frac{\lambda_s \gamma_R}{\lambda_p} \left( \sum_i F_{i,j} P_i^s \right) P_j^{p,\pm} \quad (2)$$

where  $\alpha_s$  and  $\alpha_p$  are loss coefficients for signal and pump wavelengths  $\lambda_s$  and  $\lambda_p$ , and  $\gamma_R$  is related to the spontaneous Raman scattering cross section. Note that  $\gamma_R$  and  $\alpha_{p,s}$  are assumed mode-independent. The intensity overlap integrals are defined as

$$F_{i,j} = \frac{\int I_i I_j \, dA}{\int I_i \, dA \int I_j \, dA}, \quad (3)$$

with  $I_i$  being the intensity of mode  $i$  integrated over the entire fiber cross section. Solving (1) and (2) using the undepleted pump approximation, we arrive at an expression for the on/off gain

$$G_i = \frac{P_i^s(L) \text{ (pump on)}}{P_i^s(L) \text{ (pump off)}} = \exp \left( \gamma_R L_{\text{eff}} \left( \sum_j F_{i,j} P_j^{p,+}(0) + \sum_j F_{i,j} P_j^{p,-}(L) \right) \right), \quad (4)$$

where  $L_{\text{eff}} = (1 - \exp[-\alpha_p L]) / \alpha_p$  is the effective fiber length and  $L$  is the physical fiber length. The setup used is a backwards pumped configuration, where the pump has only two different spatial profiles (corresponding to LP<sub>01</sub> and LP<sub>11</sub>), so Eq. (4) can be reduced to

$$G_i = \exp(\gamma_R L_{\text{eff}} [\eta_p F_{i,11} + (1 - \eta_p) F_{i,01}] P_p), \quad (5)$$

for the signal in mode  $i$ , where  $\eta_p$  is the degree of conversion of the pump from LP<sub>01</sub> to LP<sub>11</sub> ( $\eta_p = 0$  when all the pump power is in LP<sub>01</sub>, and  $\eta_p = 1$  when all the pump power is in LP<sub>11</sub>) and  $P_p$  is the total input pump power (in all modes). Using the setup which is described in the methods section below, 65 measurements were carried out with 5 different conversion degrees and 13 different pump power levels varying from 0 to 1200 mW for each conversion degree. From the expected form of the gain, Eq. (5), we fitted a function of the form

$$G_{01}^{(\text{dB})} = (c_1 + c_2 \eta_p) P_p \quad (6)$$

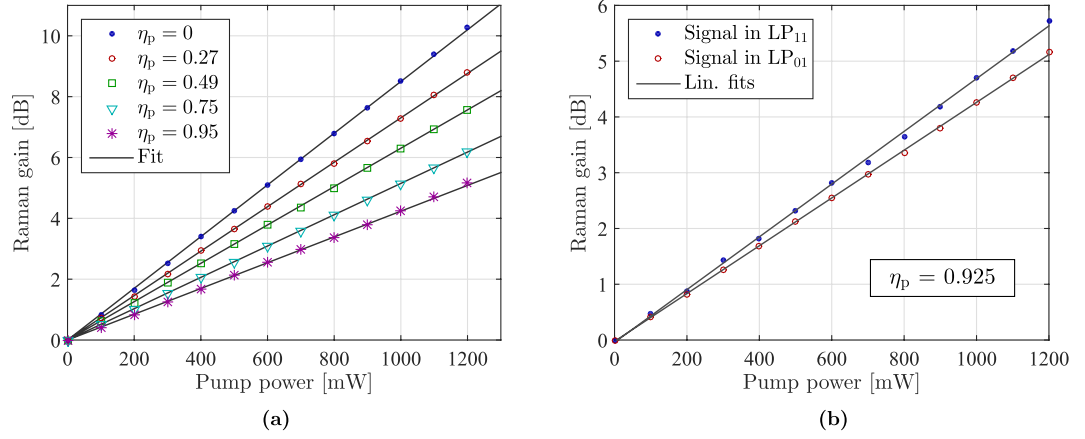
to the data, where  $c_1$  and  $c_2$  are fitting parameters. The result is presented in Fig. 1a where data and fitting lines are shown at the five different values of  $\eta_p$ . The obtained values for the fitting parameters are  $c_1 = 8.50 \text{ dB/W}$  and  $c_2 = -4.48 \text{ dB/W}$ . The theoretical expression is in excellent agreement with the obtained data with these values of the fitting parameters. From these values the ratio of the Raman intensity overlaps between the LP<sub>01</sub>-LP<sub>01</sub>-modes and LP<sub>01</sub>-LP<sub>11</sub>-modes is obtained

$$\frac{F_{01,11}}{F_{01,01}} = 1 + \frac{c_2}{c_1} = 0.47, \quad (7)$$

by comparing (5) and (6). This result agrees well with the value of 0.48 obtained from simulated mode-profiles provided by the fiber supplier.

Subsequently, the signal was coupled to the LP<sub>11</sub>-mode with the highest attainable efficiency, ( $\eta_p > 0.99$ ), and the pump was converted to the LP<sub>11</sub>-mode with an efficiency of  $\eta_p = 0.925$ , see the Methods section for details, and the Raman gain of the LP<sub>11</sub>-signal was measured vs. the input pump power. A linear function of the type

$$G_{11}^{\text{dB}} = c_3 P_p, \quad (8)$$



**Figure 1.** (a) Measured Raman gain vs. input pump power for five different pump conversion degrees,  $\eta_p$ ; the lines result from the two-parameter fit evaluated at each conversion degree. (b) Measurements of Raman gain for signal and pump in LP<sub>11</sub>. For comparison is shown the measurement with pump in LP<sub>11</sub> and signal in LP<sub>01</sub>.

	LP <sub>01</sub> -LP <sub>01</sub>	LP <sub>11</sub> -LP <sub>01</sub>	LP <sub>11</sub> -LP <sub>11</sub>
Measurement	1	0.47	0.56

**Table 1.** Measured values for overlap integrals relative to the LP<sub>01</sub>-LP<sub>01</sub> overlap.

	LP <sub>01</sub>	LP <sub>11a</sub>	LP <sub>11b</sub>
LP <sub>01</sub>	1	0.48	0.48
LP <sub>11a</sub>	0.48	0.72	0.24
LP <sub>11b</sub>	0.48	0.24	0.72

**Table 2.** Simulated overlap integrals for all modes.

was fitted to the data. From this the ratio  $\frac{F_{11,11}}{F_{01,01}}$  is calculated, taking into account the pump conversion degree. The slope obtained from the fit to the LP<sub>11</sub>-LP<sub>11</sub>-data was  $c_3 = 4.74$  dB/W. We assume wavelength independence of the overlap integrals (i.e. that the LP<sub>01</sub>-LP<sub>11</sub> and LP<sub>11</sub>-LP<sub>01</sub> overlaps are nearly identical). By comparison of Eqs (8) and (6) to (5) we note that  $c_1 = kF_{01,01}$  and  $c_3 = k(F_{01,11} + \eta_p(F_{11,11} - F_{01,11}))$  with  $k = 10 \log_{10}(e)\gamma_R L_{\text{eff}}$ . Using Eq. (7) for the ratio  $F_{01,11}/F_{01,01}$ , these two expressions can be rearranged to give

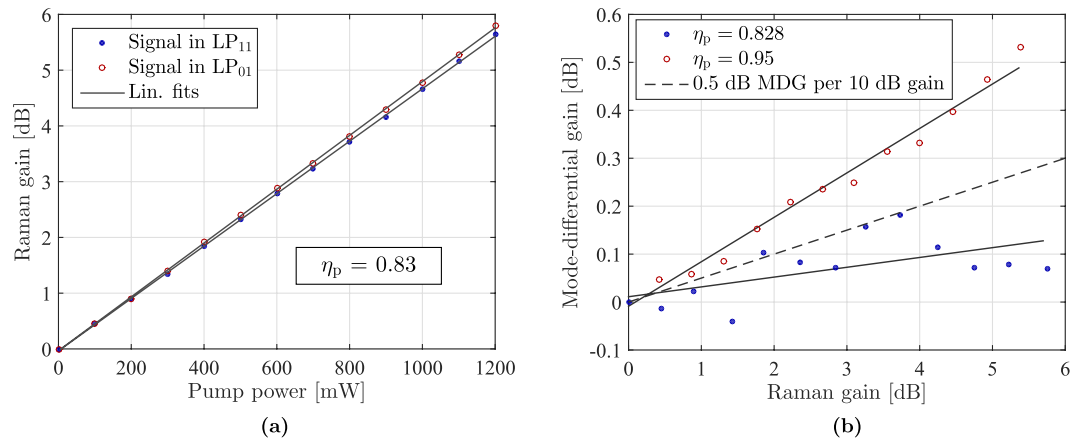
$$\frac{F_{11,11}}{F_{01,01}} = \frac{c_3}{c_1 \eta_p} - \frac{1 - \eta_p}{\eta_p} \left( 1 + \frac{c_2}{c_1} \right) = 0.56. \quad (9)$$

This is compared to the simulated values for LP<sub>11a</sub>-LP<sub>11a</sub> and LP<sub>11a</sub>-LP<sub>11b</sub> of 0.72 and 0.24, respectively. The measured overlap is, as expected, an intermediate value that depends on the mode-coupling within the LP<sub>11</sub> mode-group. In Table 1 the measured overlaps are summarized, and in Table 2 the simulated overlaps are shown. Notice that the overlaps are normalized so that the LP<sub>01</sub>-LP<sub>01</sub>-overlap equals one.

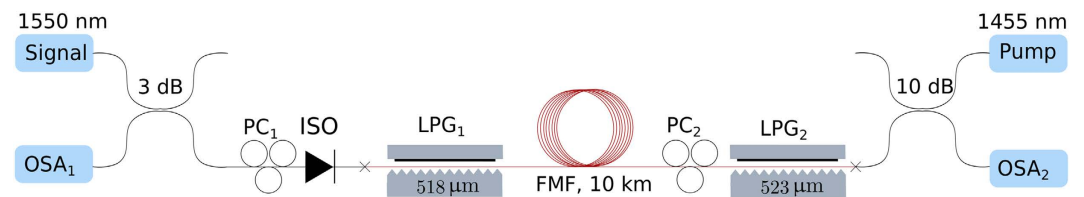
**Mode-equalized Gain Based on Measured Overlaps.** Since the LP<sub>11</sub>-LP<sub>11</sub> and LP<sub>11</sub>-LP<sub>01</sub> intensity overlaps often turn out to be very similar in FMFs, relatively low differential gain can be obtained by simply launching the pump completely into LP<sub>11</sub>. This was experimentally verified by R. Ryf *et al.*<sup>6</sup> where a differential gain of 0.5 dB per 10 dB of gain was observed. For the fiber used in this work, such a scheme results in a differential gain of 1 dB per 10 dB of gain as obtained from the data shown in Fig. 2b (the differential gain in the figure is slightly lower since the pump is only converted 95% into LP<sub>11</sub>). Using our knowledge of the intensity overlap integrals, the condition for equal signal gain across the two signal-modes,  $G_{11} = G_{01}$ , can be written as

$$\eta_p F_{11,11} + (1 - \eta_p) F_{01,11} = \eta_p F_{01,11} + (1 - \eta_p) F_{01,01}. \quad (10)$$

This equation can be solved, using the experimentally obtained values for the ratios  $F_{11,11}/F_{01,01}$  and  $F_{01,11}/F_{01,01}$ , to obtain an equal-gain pump conversion of



**Figure 2.** (a) Raman gain for both a LP<sub>01</sub> and LP<sub>11</sub>-signal with a pump in the mixture of 83% LP<sub>11</sub> and 17% LP<sub>01</sub> demonstrating near-equal gain for the two signals. (b) MDG between the two signal modes for pump almost completely converted to LP<sub>11</sub> and pump in the mixture of 83% LP<sub>11</sub> and 17% LP<sub>01</sub>. A line for 0.5 dB gain difference per 10 dB gain is included for reference.



**Figure 3.** The experimental setup used for all measurements. ISO: Isolator, OSA: optical spectrum analyser, PC: polarization controller, LPG: long period grating, FMF: few-mode fiber. Red lines signify FMF and black lines single mode fiber with crosses indicating splices. The number on the gratings indicate pitch.

$$\eta_{p,eq} = \frac{1 - F_{01,11}/F_{01,01}}{1 + F_{11,11}/F_{01,01} - 2F_{01,11}/F_{01,01}} = 0.854 (=8.35 \text{ dB conversion}). \quad (11)$$

In Fig. 2a the results of measuring a signal launched first completely in LP<sub>01</sub> and then completely in LP<sub>11</sub> with a pump conversion of  $\eta_p = 0.83$ , i.e. slightly below the optimal value, are shown. From the figure it is clear that very little mode-dependent gain remains (compare with Fig. 1b). The mode-differential gain as a function of the mean gain is seen in Fig. 2b, showing a residual MDG of only 0.25 dB per 10 dB of Raman gain as obtained from the fitted lines. This differential mode gain is, to the best of our knowledge, the lowest that has so far been experimentally demonstrated. The reason for the fluctuation in MDG is most likely due to mode coupling between LP<sub>11a</sub> and LP<sub>11b</sub>. The LPG preferentially couples to the LP<sub>01</sub> mode that we detect in the optical spectrum analyzer (OSA), as explained in the Methods section. This means that any mode coupling between LP<sub>11a</sub> and LP<sub>11b</sub> shows up as a small variation in the measured amplified signal. In the  $\eta_p = 0.83$  (blue dot) measurement the back coupling is slightly more unstable compared to the  $\eta_p = 0.95$  (red circle). This is due to the different configuration of the back coupling LPG.

## Methods

The intermodal Raman gain is measured using the experimental setup shown in Fig. 3. The setup is a distributed backwards pumped multi-mode Raman amplifier with a CW laser operated at 1550 nm as the signal source, and an unpolarized 1455 nm Raman fiber laser used for optical pumping. The characterized fiber is a 10 km, 2-moded graded-index fiber.

**Higher-Order Mode excitation.** The excitation of higher-order modes is achieved by use of mechanically induced LPGs, which are created by pressing the fiber between a periodically grooved aluminum block and a rubber pad. This creates a periodic perturbation in the fiber index, which induces mode coupling if the pitch of the induced gratings matches the difference in propagation constants of the modes<sup>18</sup>.

Using a broadband supercontinuum source at the signal input the mode-converted wavelengths are observed in the OSA<sub>2</sub> as a drop in the power spectrum due to the FMF to single mode fiber splice working as a mode filter. The effective pitch of the LPG is changed by adjusting the angle of the grooves with respect to the fiber, until maximum mode-conversion is achieved at the signal wavelength. The use of a supercontinuum source for calibration is not strictly necessary if the difference in propagation constant for the modes of interest is known, but it facilitates

the excitation process. Based on the knowledge of the propagation constants the pitch for the pump wavelength was calculated to be 527  $\mu\text{m}$ , which is in excellent agreement with the 523  $\mu\text{m}$  pitch experimentally observed at maximum conversion. The LPGs are polarization dependent<sup>18</sup>, so a polarization controller (PC) is used to optimize conversion of the polarized signal source. After propagation through the fiber the signal is converted back to the fundamental mode using a second LPG.

From standard mode-coupling theory the coupling strength between the modes in a step-index fiber is given by<sup>19</sup>

$$K(z) = \frac{\pi}{\lambda n_{\text{core}}} \frac{\int \Delta\varepsilon(r, \phi, z) \psi_1(r, \phi) \psi_2(r, \phi) \, dA}{\int \psi_1^2(r, \phi) \, dA}, \quad (12)$$

where  $\psi_{1,2}$  are the scalar mode profiles of the fiber. Since the grooves of the mechanical block are only applied to the fiber from one direction, the perturbation  $\Delta\varepsilon(r, \phi, z)$  is asymmetric with respect to this direction. Since the  $\text{LP}_{01}$  mode is a circularly symmetric mode, we expect that mainly the  $\text{LP}_{11}$  mode which is spatially asymmetric with respect to the perturbation direction is excited in the induced grating. However, since we use an unpolarized pump, both polarizations of this spatial mode are excited resulting in an almost equal excitation of the four full-vectorial modes ( $\text{TE}_{01}$ ,  $\text{TM}_{01}$ ,  $\text{HE}_{21a}$  and  $\text{HE}_{21b}$ ) that constitute the pseudo- $\text{LP}_{11}$  modes. The strong coupling between these modes is expected to quickly smooth out any difference in the excitation<sup>17</sup>. Thus, following a similar approach as Antonelli *et al.*<sup>20</sup>, we only consider the excitation of the quasi-degenerate groups of modes,  $\text{LP}_{01}$  and  $\text{LP}_{11}$ , consisting of two and four nearly degenerate modes, respectively. In this regard, the measured overlaps are essentially an average over these groups.

**Characterization of fiber under test.** For all measurements the signal power launched is 0.4 mW, and the launched pump power is varied from 0 to 1200 mW. For each pump power the on/off gain is measured by OSA<sub>2</sub>. The ratio of the  $\text{LP}_{01}$ - $\text{LP}_{01}$  and  $\text{LP}_{01}$ - $\text{LP}_{11}$  overlaps is found with the signal in  $\text{LP}_{01}$  and the pump in varying mixtures of both  $\text{LP}_{11}$  and  $\text{LP}_{01}$  by adjusting  $\text{LPG}_2$  to the desired pump mode conversion.

For the  $\text{LP}_{11}$ - $\text{LP}_{11}$  gain measurement  $\text{LPG}_1$  and  $\text{PC}_1$  were adjusted to obtain more than 99% signal conversion, and  $\text{LPG}_2$  was adjusted to obtain a maximum of  $\eta_p = 0.92$  pump conversion; The lower pump conversion is due to the pump being unpolarized. The  $\text{LPG}_2$  conversion bandwidth is large enough such that, by optimizing  $\text{PC}_2$ , 12 dB of the signal is converted back to  $\text{LP}_{01}$ . The back conversion is necessary due to the mode-filtering effect of the single-mode to multi-mode fiber splice. The gain of the back converted signal is the  $\text{LP}_{11}$ - $\text{LP}_{11}$  gain.

**Equal modal gain measurement.** To equalize the modal gain, we first adjust  $\text{LPG}_2$  so that we are pumping in a combination of the  $\text{LP}_{11}$  and  $\text{LP}_{01}$  modes very close to the optimal value 85% conversion as obtained from the previous measurements, see Eq. (11). We then first adjust  $\text{LPG}_1$  and  $\text{PC}_1$  to maximize signal conversion ( $\eta_p > 0.99$ ) and measure the gain of this mode. Then  $\text{LPG}_1$  is lifted so that the signal is a pure  $\text{LP}_{01}$ -mode and the gain for this mode is measured. The difference in the gain for these two signal-modes then gives the mode-differential gain.

## Conclusion

We have experimentally characterized the intermodal Raman overlaps in a few-mode fiber by varying the launched pump power and the conversion efficiencies of the pump and signal using mechanically induced long-period gratings for mode excitation. The overlap integrals (relative to the  $\text{LP}_{01}$ - $\text{LP}_{01}$  overlap) for all modal combinations were obtained in this way for a specific few-mode fiber. By use of the obtained overlaps, it was further demonstrated how a mode-differential gain of only 0.25 dB per 10 dB overall gain is obtained by pumping in a specific combination of the  $\text{LP}_{11}$  and  $\text{LP}_{01}$  modes. In the specific few-mode fiber under test, the differential gain was shown to be significantly lower when pumping in the determined combination of modes compared to when pumping only in  $\text{LP}_{11}$ .

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## Acknowledgements

The authors acknowledge financial supported for the research by The Danish Council for Independent Research, research grant: DFF – 4184-00433, and InnovationsFonden for funding the e-space project (#0603-00514B) and also the center of excellence: Silicon Photonics for Optical Communications granted by the Danish National Research Foundation (DNRF123).

## Author Contributions

E.N.C. and J.G.K. performed experiments and wrote the manuscript. S.M.M.F., M.A.U.C. and K.R. contributed to theory and conceiving experiments. All authors reviewed and revised the manuscript.

## Additional Information

**Competing financial interests:** The authors declare no competing financial interests.

**How to cite this article:** Christensen, E. N. *et al.* Experimental characterization of Raman overlaps between mode-groups. *Sci. Rep.* **6**, 34693; doi: 10.1038/srep34693 (2016).



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