A Two-Mode Cladding-Pumped Ytterbium-Doped Fibre Amplifier

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Abstract Summary

Using cladding-mode pumping, simultaneous amplification of both the fundamental and second modes is demonstrated in an ytterbium-doped, two-mode fibre. A gain of 30dB was measured over 2 metres of fibre using 1 watt of pump power.

Keywords- few-mode fibres; optical amplification; spatial-mode-division-multiplexing.

I. Introduction

With the information explosion currently occurring in society, which is, for instance, driving an 80 per cent per annum growth in data storage, data transmission bandwidth is currently of primary concern. In the interests of increasing data transmission density, there is currently considerable interest in mode-division multiplexing. In addition, there is interest in high-power laser amplifier construction using large mode area fibres. Both of these areas require a detailed understanding of the nature of power amplification of the higher-order modes, with the former having the aim of evenly spreading power amongst modes and the latter having the aim of maximising the power in the fundamental mode.

The objective of this work is to develop a power amplification measurement technique to quantify the power in each mode of a few-mode fibre using cladding mode pumping for their amplification. This would achieve the business goal of developing a fibre power meter for measuring modal power amplification that can be used for measuring the amplification of power in the fundamental mode and the higher-order modes in a low-power, cladding-pumped data transmission system Erbium-Doped Fibre Amplifier (EDFA) or Ytterbium-Doped Fibre Amplifier (YDFA) to determine the evenness of power spread across the modes. It would also achieve the business goal of a fibre power meter for a cladding pumped high power laser to determine the degree of bias of power toward the fundamental mode.

II. Previous Work

A. Few-Mode Fibre Transmission

Reference [1] claims to have demonstrated transmission of 6x56 Gb/s over few-mode fibre, using bulk optics to take the input signals and process them into each of the modes and a 6x6 Multiple Input Multiple Output (MIMO) electronic device as a part of the de-multiplexer to untangle the 6 streams extracted at the far end, and [2] claim to have conducted two mode transmission at 100Gb/s for each mode over a 40km long few-mode fibre, also using MIMO at the output.

Reference [3] demonstrated of the transmission of mode division multiplexed data from three 88-channel DWDMs that are fed into the LP_{01}, the LP_{11o} and LP_{11e} modes of a 50km length of few-mode fibre. It achieved a transmission of 26.4Tb/s. They used phase plates for the few-mode modulation and demodulation, and a 6x6 MIMO device for the receiver.

After [4] looking at an approach using elliptical fibre, an alternative approach was proposed by [5] that is applicable to very few (up to four or five) modes that uses asymmetric multi-arm Y-junctions. This approach, while modelled at 1550nm (for convenience), could be applied to existing data centre deployment of legacy single-mode fibre by reducing the wavelength from 1550nm to a level to yield two or three modes. This should yield a low cost solution that could be readily and cheaply integrated into a SFP transceiver device for existing data centres, while also being a practical alternative at the 1550nm wavelength for longer distance networks.

B. Power Measurement

A design was reported by [6] that uses a polarisation analysis instrument made up of a quarter-wave plate in front of a polarising beam splitter, and a mode-selective 3-mirror ring resonator that is used for mode analysis. They energise a 25µm core diameter fibre at an offset and phase that produces 2 modes.

Reference [7] produced a design for measuring the power of each higher-order mode in a few-mode fibre as well as providing a high quality image of the fibre modes. Analysing large mode area fibres, their system provided better accuracy in determining beam quality than would be obtained by the traditional M2 parameter measurement. Their machine had a Ytterbium-based broadband optical source, the test fibre, 2 lenses for the image, a polariser instrument, a single-mode probe fibre, an x-y plane scanning platform, an optical spectrum analyser and a computer for information analysis.

III. Theory

A. Total Power in Each Mode

The amplification can be modelled with modes. Referring to Fig. 1, the source electric field, E_s is applied to the calculation using a normalised fibre radius (where $R=r/\rho$) with

R=1 (the boundary between the core and the cladding). From [9], given that dA=rdφdr, we have (1), where the denominator can be ignored for the purposes of the amplification. From this, the amplitude is calculated as per (2).

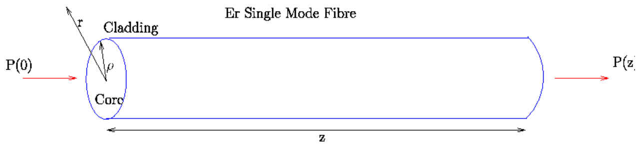

Figure 1. Parameter arrangement for the analysis of power in the modes in a length of amplifying fibre.

$$\psi_m = \frac{a_m J_m(U_m R) dA}{J_m(U_m)} \tag{1}$$

In (1), a_m is the amplitude of the mth mode, J_m is the Bessel function of the first kind for the mth mode, U_m is the core modal parameter, and A is the area. The gain is represented by the application of amplification as per (2), where the gain coefficient, γ, is calculated from a trial.

$$P(z) = P(0)\exp(+\gamma z) \quad \gamma = \eta \frac{2\pi}{\lambda} n_{(i)}; \quad n_{(i)} < 0 \tag{2}$$

Here, the fraction of power in the core, η, for a weakly guiding step profile fibre is he standard formula [8, pp 313] where $n_{(i)}$ is the (complex) refractive index that describes the fibre gain.

From this, a cutback experiment can be conducted and the measured gain can be related to the ideal via (3).

$$dB = 10\log_{10}\frac{P(z)}{P(0)} = 10\gamma z\eta \log_{10} \mathrm{e} \tag{3}$$

For the second run, using $P_2(z)=P_2(0)e^{\gamma_2 z}$, the gain coefficient can be worked out from (2) as $\gamma_2 = \eta_2 \frac{2\pi}{\lambda} n_{(i)}$.

Mode Intensity Profile

While previous researchers (e.g. [9]) caution that the far field is different to the near field, it might be reasonable to use the near field model and match the amplitude variables to approximately match the profiles. The far-field intensity profile is effectively a simplification of the near field, and radiation from a fibre end, which is effectively a source point optical antenna, is an out-going spherical wave with a directional weighting function [10, pp 28-29]. Using a goniometric radiometer or similar intensity measurement tool, it is straightforward to measure the far field at the end of a fibre. Calibrating against total power from a power meter, this approach should be accurate enough to determine the relative power in each mode.

The analysis is based on (4), where P is the power, r and φ are the polar coordinates of a point on the end of the fibre, I(r,φ) is the intensity at that point and the integral is taken over the entire area A [11]. By approximately matching the intensity profiles, the total relative modal intensity values is known and therefore the total power for each mode can be determined.

$$P = \int_{A_\infty} I(r,\phi)dA = \int_0^\infty \int_0^{2\pi} I(r,\phi) r d\phi dr \tag{4}$$

The total intensity profile $I_T(r,\varphi)$ is the sum of the individual intensity profiles $I_m(r,\varphi)$ for each mode m that is modified by an amplitude scaling factor for that mode $a'_m = \sqrt{\frac{n_{co}}{2}}\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/4} a_m$ (where a_m is the intensity amplitude) and a length-dependent phase factor as per (5).

$$I_T(r,\phi) = \sum_{m=1}^{n} |a'_m|^2 I_m(r,\phi) + 2\sum_{m,=1}^{n}\sum_{k=m+1}^{n}\left(a'_m\sqrt{I_m(r,\phi)}a'_k\sqrt{I_k(r,\phi)}\cos\left((\beta_m-\beta_k)z\right)\right) \tag{5}$$

Modal intensity, as a function of radius and angle, is given by the standard formula for as defined in [11], [8].

Combining (4) to (5) and substituting in the standard formulae results in (6), where φ is given by (7), J_m is the Bessel function of order m for mode m, K_m is the modified Bessel function of order m for mode m, β is the propagation constant, ρ is the core radius, the transverse spatial core parameter of the guided mode field, U, and the transverse spatial decay parameter of the mode field in the cladding region, W are given by the standard formulae, and k is the free space wave number, n_{co} is the core refractive index and n_{cl} is the cladding refractive index.

$$P = \int_{A_\infty}\left(\sum_{m=1}^{n}\left(\frac{n_{co}}{2}\left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}}|a_m|^2 \left[\begin{cases}\frac{J_m^2\left(U\frac{r}{\rho}\right)}{J_m^2(U)}\cos^2(m\phi) & r<\rho\\ \frac{K_m^2\left(W\frac{r}{\rho}\right)}{K_m^2(W)}\cos^2(m\phi) & r>\rho\end{cases}\right]\right)+\varphi\right)dA \tag{6}$$

$$\varphi = 2\sum_{m=1}^{n}\sum_{k=m+1}^{n}\left(\frac{n_{co}}{2}\left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} a_m a_k\cdot\right. \left[\begin{cases}\left(\frac{J_m^2\left(U\frac{r}{\rho}\right)}{J_m^2(U)}\frac{J_k^2\left(U\frac{r}{\rho}\right)}{J_k^2(U)}\cos^2(m\phi)\cos^2(k\phi)\right)^{\frac{1}{2}} & r<\rho\\ \left(\frac{K_m^2\left(W\frac{r}{\rho}\right)}{K_m^2(W)}\frac{K_k^2\left(W\frac{r}{\rho}\right)}{K_k^2(W)}\cos^2(m\phi)\cos^2(k\phi)\right)^{\frac{1}{2}} & r>\rho\end{cases}\right] \left.\cos\left((\beta_m-\beta_k)z\right)\right) \tag{7}$$

As the fibre output may be rotated at an angle α compared to the input end, then, ignoring any potential variation in the mode caused by the fibre bending and stress induced polarisation that [1] asserts takes place, (6) can be modified to include a phase component on the end.

IV. RESULTS

Power Measurement System

A block diagram of the total system is at Fig. 2. Key components of the system are the Photon Inc. Goniometric Radiometer modified with a face plate and launch jig, associated Photon Inc. viewer software, the 3-dimensional intensity extraction software and the intensity profile matching software's modelled and measured intensity output.

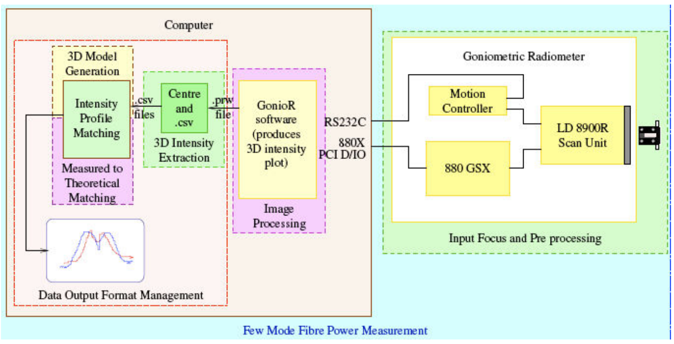

Figure 2. Total System Block Diagram, showing how hardware and software within hardware maps on to the functional decomposition.

Test Set-up

To test the effectiveness of the power measurement system, for non-amplified signals, the system is set up to measure the power in a 2-mode fibre as per Fig. 3, where the fibre is put through a bend radius test using the mandrel as a template, but with the gain fibre out of circuit. For the amplified signal, the system is set up with a segment of gain fibre in circuit and is also put through a bend radius test.

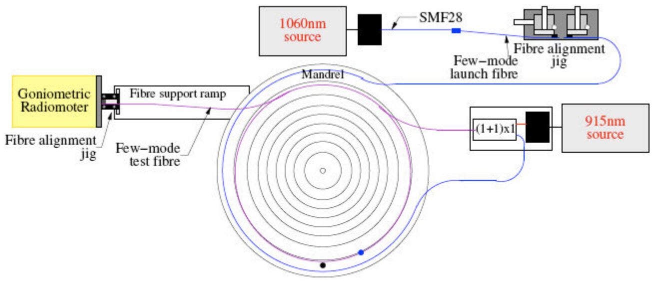

Figure 3. Layout of the system for a bend radius test of 2-mode fibre undergoing few-mode power amplification, showing up to the Goniometric Radiometer interface to the system.

Test Results

A plot of measured against calculated values is at Fig. 4. The original sample set had just 3 of the samples separated out to be used to calibrate against. With R^2>0.9, the fit is reasonable. Errors were seen to vary by between ±1% and ±10%, probably mostly due to observed fluctuations. The graph implies, and the later power amplification tests suggest that, the results may be more accurate if separate calibration constants were used for the different number of modes.

A bend radius test was done on Nufern LMA-GSF-15/123 few-mode fibre, injecting one and two modes, and then on the LMA-GSF-15/123 few-mode fibre joined to a length of Nufern LMA-YDF-15/130 Ytterbium-doped fibre with amplification applied. The results for both cases are graphed at Fig. 5, where the power is that calculated using the Intensity Profile Matching algorithm and the angle is relative to the goniometric radiometer's x-axis. As fibre orientation to the goniometric radiometer was not maintained in the amplified fibre suite of tests, there was a high variation in angle.

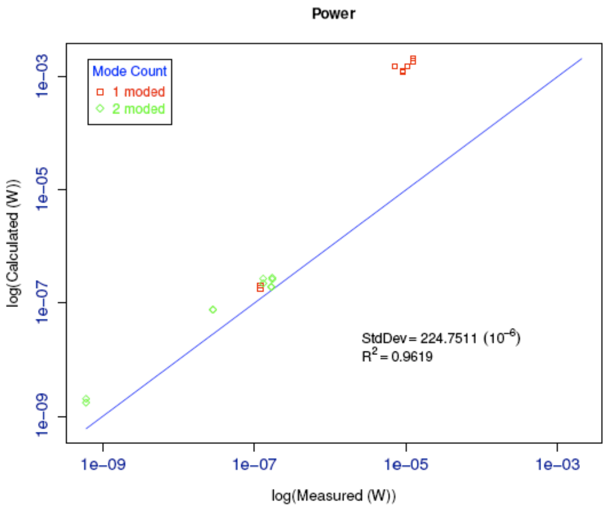

Figure 4. Power level accuracy test.

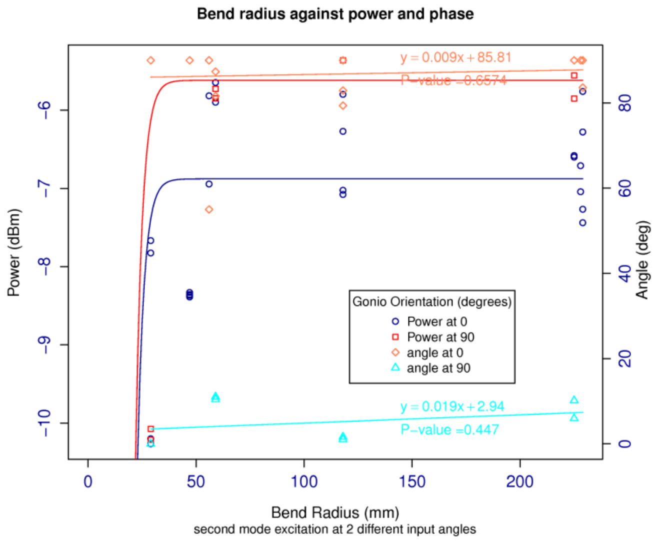

Figure 5. Bend radius tests for the unamplifed fibre.

The second mode angles were quite linear with bend radius, with deviation of less than ±10° for a particular orientation in the no amplification case of Fig. 5a. Amplifying two modes through a 2m length of cladding-pumped YDFA demonstrated a higher degree of amplification of the fundamental mode over the second mode, but with a strong second mode signal containing more than 60% of the total power, amplification of the fundamental mode is only 5% or ~2dB greater than for the second mode. This is because, just as amplification has a logarithmic relation to pump power, so amplification is dependent on the incoming seed signal power. Also, when comparing the degree of gain achieved out of the same amount of pump power for a single injected mode and two injected modes as shown in Fig. 6, two modes did fare better than one mode. This is because more amplification takes place with two modes as the fields extend further into the cladding than with a \single mode and the bulk of the fields therefore got greater power level exposure to pump power energy.

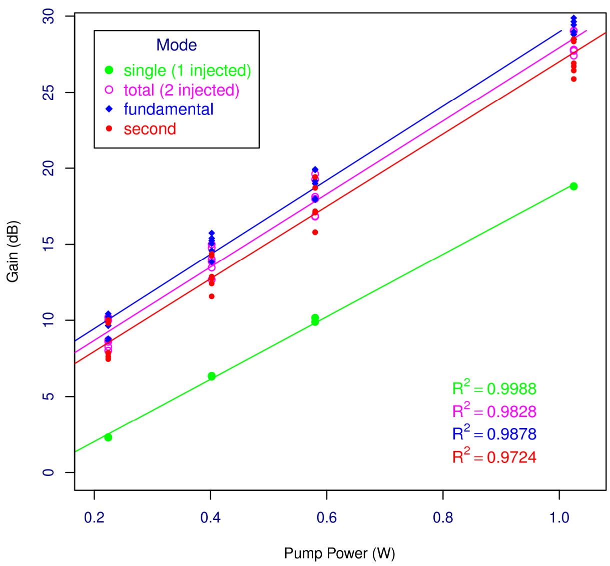

Figure 6. Ytterbium Doped Fibre Amplifier (YDFA) pump power to gain relationship for 1 and 2 injected modes.

Applying the formula of (6) for 2m of gain fibre, the gain coefficient for each pump power value for single- and for two-modes is plotted in Fig. 7. This plot shows that the gain coefficient is linear with pump power, as implied in the formulae of Section III-A, that is, $\gamma \propto P_{pump}$ and therefore $n_{(i)} \propto P_{pump}$ as is expected.

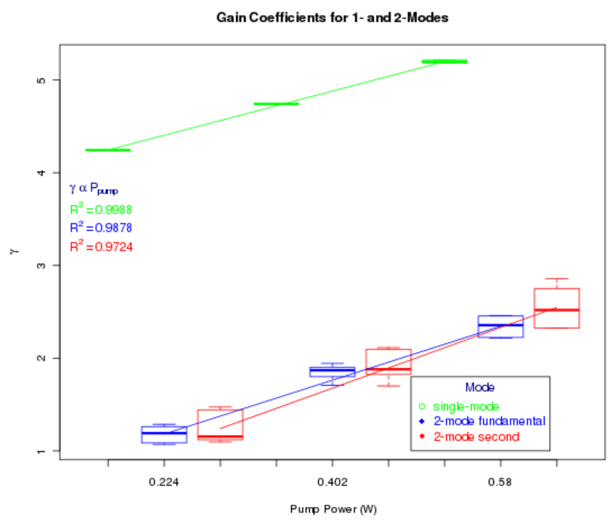

Figure 7. Gain Coefficient.

V. Conclusions

Testing on the approach of calculating the near-field model and then mapping it out to the far-field measured profile in order to determine the mode parameters works with an adequate degree of accuracy for the purposes of comparison of power in each of the modes, although the approach can do with some refinement. Bend loss experiments demonstrated that, above the radius where power is stripped out of the core, bending does not noticeably affect the second mode any more than it does the fundamental mode. Further, for two and probably more modes, the bend radius calculation for single mode provides an adequate guide. The observation that with higher initial amplitudes in the higher order modes, as was observed with 2-mode fibre, gives good amplification of those higher order modes means there is an opportunity to exploit this feature in order to even out or otherwise control power amplification of the modes.

References

[1] S. Randel, R. et al., "6x56-gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6x6 mimo equalization," Optics Express, vol. 19, no. 17, pp. 16 69716 707, Aug 15 2011, last accessed 21/11/2011.

[2] C. Koebele, M. et al., "Two mode transmission at 2x100gb/s, over 40km-long prototype few-mode fiber, using lcos-based programmable mode multiplexer and demultiplexer," Optics Express, vol. 19, no. 17, pp. 16 59316 600, 15 Aug 2011, last accessed 21/11/2011.

[3] E. Ip, N. et al., "88x3x112-gb/s wdm transmission over 50 km of three-mode fiber with inline few-mode fiber amplifier," in Optical Communication (ECOC), 2011 37th European Conference and Exhibition on, Sept. 2011, pp. 1-3.

[4] N. Riesen, J. Love, and J. Arkwright, "Few-mode elliptical-core fiber data transmission," Photonics Technology Letters, IEEE, vol. 24, no. 5, pp. 344 346, 1 March 2012.

[5] J. Love and N. Riesen, "Single-, few-, and multimode y-junctions," Lightwave Technology, Journal of, vol. 30, no. 3, pp. 304 309, 1 Feb 2012.

[6] N. Andermahr, T. Theeg, and C. Fallnich, "Novel approach for polarization-sensitive mode measurement and its application in few-mode fiber amplifier systems," in Lasers and Electro-Optics, 2008 and 2008 Conference on Quantum Electronics and Laser Science. CLEO/QELS 2008. Conference on. IEEE, May 2008, pp. 1-2.

[7] J. W. Nicholson, A. D. Yablon, S. Ramachandran, and S. Ghalmi, "Spatially and spectrally resolved imaging of modal content in large-mode-area fibers," Optics Express, vol. 16, no. 10, pp. 72337243, 12May 2008.

[8] A. W. Snyder and J. D. Love, Optical waveguide theory. London; New York: Chapman and Hall, 1983, reprint available from Klewer Academic Publishers.

[9] V. Rodriguez, "Half power beamwidth and high power measurements: The dangers of using far field approximations in the near field," in Electromagnetic Compatibility, 2008. EMC 2008. IEEE International Symposium on. Detroit, MI, U.S.A.: IEEE, Aug. 2008, pp. 1-6.

[10] R. S. Elliott, Antenna Theory and Design, revised ed., ser. IEEE Press Series on Electromagnetic Wave Theory, D. G. Dudley, Ed. Los Angeles, USA: IEEE Press/John Wiley & Sons, Inc., 2003, original edition published in 1981.

[11] J.-M. Liu, Photonic Devices. The Edinburgh Building, Cambridge CB2 8RU, UK: Cambridge University Press.