Characterization of High Speed Optical Detectors for Purpose of OM4 Fibre Qualification: Selective Mode Detection

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Keywords: High Speed Optical Fibre, High Speed Detector, Optical Fibre Qualification.

Abstract: The most important characterization of OM4 fibre is the ‘Differential Mode Delay’ (DMD) measurement. The measured DMD profile is some kind of ‘roadmap’ of the OM4 fibre; it contains all relevant data from which the main optical parameters are computed (for instance ‘Effective Modal Bandwidth’). Most requirements for the measurement equipment are well defined within standardization documents. However the requirements for the detector are still under discussion. This paper shows the state of the art of commercially available detectors (high speed optical electrical converters, fibre coupled) from different manufacturers. A method to characterize these detectors is suggested, and it shows the ‘ideal’ detector is not yet commercially available.

1 INTRODUCTION

In today’s world the need for high speed data transmission is growing. In high performance data centers multimode fibres are commonly used. Today the operational wavelength is 850 nm, but ‘wide band multimode fibres’, covering the range 850 nm to 950 nm (likely to be OM5) are being developed and tested in systems (CommScope, 2015, Molin 2014). Some publications exist to discuss the specifications that wide band fibre should reach 950 nm (Pimpinella, 2014, Bigot, 2015)). These fibres are qualified by a tightly standardized measurement method called ‘Differential Mode Delay’ (DMD) (Oh, 2012, TIA, 2003). The main parameter considered is the ‘Effective Modal Bandwidth’ (EMB). The EMB is computed from the ‘un-normalized DMD profile’ (TIA, 2003, IEC, 2017). The specification for the EMB value becomes more relaxed when the wavelength increases from 850 to 950 nm. This is caused by the fact that the ‘penalty’ caused by Chromatic Dispersion goes down. At 850 nm the EMB specification is 4700 MHz.km, at 950 nm EMB is specified at 2450 MHz.km (note: precise value are still under discussion at *IEC* and *TIA*).

When the fibre is optimized at 850 nm, the EMB will be much higher than the specified value. However, when the range 850 nm to 950 nm is considered, the EMB values at 850 nm and 950 nm will be closer to the specified values. This means the precision of the DMD measurement method becomes more relevant. On the launching side (side of the fibre where the laser pulses are launched into), the laser pulse characteristics and the exact position and size of the launch spot are very relevant. On the detector side, two properties are relevant. First of all the detector must be sufficiently fast to detect small changes of the laser pulse shape after travelling through the fibre under test. If fibres are measured close to the fibre length used in systems, the laser pulse must be very narrow in time domain (and also in wavelength domain). A typical value for the Full Width Quarter Max (FWQM) of the laser pulse is 10 ps. A typical value for the detector bandwidth to proper detect this pulse is 25 GHz. The FWQM of the pulse detected by such a detector will be typical 35 ps (referred to as ΔT_{REF}).

Secondly, the detector must detect all the modes guided by the fibre under test. The detector response should be close related to the actual spatial and angular power distribution leaving the fibre under test. High speed detectors often tend to have a sensitive area smaller than the field leaving the fibre under test. The speed of the detector drastically reduces when the diameter of the sensitive area gets larger (Hui, 2012). To catch all the light that leaves the fibre under test, the internal fibre pigtail of the

Achten, F. and Molin, D.
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DOI: 10.5220/0006541201410147
In *Proceedings of the 6th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2018)*, pages 141-147
ISBN: 978-989-758-286-8
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detector may consist of a tapered or lensed core. The consequence of such a structure is some light will leave the internal fibre pigtail from the side, and so it will not reach the sensitive area of the detector. This causes ‘selective mode detection’. Sometimes the internal fibre pigtail is bended to fit the small housing. This will introduce macrobend losses. As far as we know, no commercial available detector exists that uses a ‘bend insensitive’ fibre design as the internal fibre pigtail. Another cause of selective mode detection may be imperfections of the sensitive area. If the detector suffers from selective mode detection, the measured DMD profile of the OM4 fibre under test is not theoretically correct, and as a consequence the computed EMB value isn’t correct either.

This paper describes a method to characterise a detector, so it can be used to qualify OM4 fibre. The method is tested on five different detectors from different manufacturers. These detectors are all specified for multimode fibre, with a very high optical bandwidth of at least 10 GHz. A very high bandwidth is mandatory to qualify short length of OM4 fibre, for instance close to the maximum system length of 400 m. All detectors are fibre pigtailed with a 50 or 62.5 µm core Graded Index fibre. Also a low bandwidth detector is used as a reference. This detector cannot detect the individual pulses (too slow), but can measure the power distribution on a near DC level. Two of the used detectors were developed for 850 nm pulse measurement (so are not suited to qualify wide band multimode fibres up to 950 nm). For now the detectors are investigated at 850 nm, but the same method (for the 950 nm sensitive detectors) can be used for other wavelengths in the range 850 - 950 nm.

2 CHARACTERIZATION METHOD

To characterize a detector, a special designed optical fibre is used. Referred to as ‘mode separating fibre’. Regular multimode fibres are designed with an ‘Alpha Profile’ refractive index core (Oh, 2012). If the Alpha value (α) is optimized for a particular wavelength (OM4: 850 nm), and the refractive index profile is very accurate, the EMB reaches very high values at that particular wavelength. This means all launched modes reach the detector at the same time after travelling through the fibre. The pulses are shaped exactly equal as launched into the fibre (assuming a short fibre length of max 1 km, so Chromatic Dispersion effects can be neglected). A typical value for α is 2.0. The special designed optical fibre (‘mode separating fibre’) has an α of 1.6. The profile is shown in Figure 1.

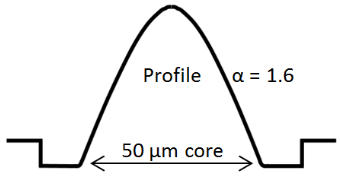

Figure 1: refractive index profile of the special designed fibre (’mode separating fibre’).

Because of the low α, the mode groups experience different times of flight through the fibre. This can be clearly seen on the resulting (normalized) measured DMD profile of Figure 2b (used is a Titanium Sapphire Mode Locked laser, 10 ps pulses, 850 nm). Figure 2a shows a simulated DMD profile on an ‘ideal’ α = 1.6 fibre. The simulation model is described in (Gholami, 2011). The method (and equipment requirements) to get a fibre DMD profile is described in detail in *TIA* and *IEC* documents (TIA, 2003, IEC, 2017). The 18 mode groups reach the fibre end at clear different moments in time. So one can derive the positions in time of the mode groups leaving the fibre, and the power of the pulses present within each mode group launched at different radial offset positions. If the α = 1.6 fibre is ‘perfect’ (equal to the input to the simulation model), the difference between the detected DMD profile and simulated DMD profile is a measure for detector performance. The closer both DMD profiles, the better detector performance (it then detects all mode groups leaving the α = 1.6 fibre). The used length of the α = 1.6 fibre (mode separating fibre) is 550 m.

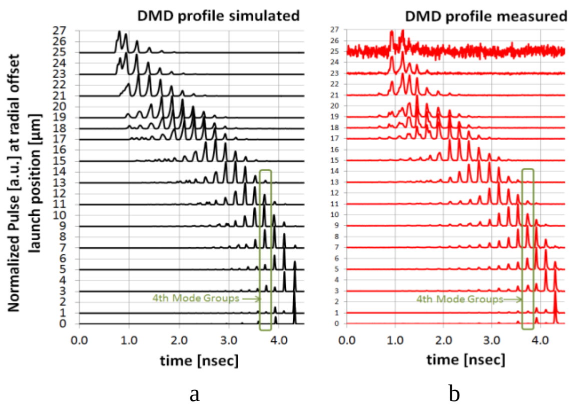

Figure 2: simulated and measured DMD profile after 550 m of the ’α = 1.6 fibre’ (mode separating fibre). 18 Mode Groups are visible and clearly separated in time.

3 MODE SEPARATING FIBRE

In Graded Index (GI) multimode fibres, the modes are sorted into mode groups. Modes of the same mode group exhibit nearly the same group index and the group index difference with its neighbour. Thus the time of flight differences are nearly the same for all mode groups. This difference of time of flight between consecutive mode groups is at first order a function of the alpha value (α), the numerical aperture (NA) or Delta (Oh, 2012), the core diameter and the wavelength of operation (λ). And at second order a function of the dopant content (full Germanium, full fluorine or a Germanium & Fluorine co-doping).

For the mode separating fibre, the α value is adapted so that the mode groups experience a clear different time of flight when travelling through the fibre. Visible by performing a DMD measurements at a specific minimal fibre length. This condition can be expressed as follows:

$$\frac{|\Delta\tau| \cdot L}{\Delta T_{REF}} > X$$

Where $\Delta\tau$ is the time delay difference between consecutive mode groups in ps/m, L is the minimum fibre length to use in the DMD measurements in m, ΔT_{REF} is the Full Width Quarter Max (FWQM) of the 'reference' pulse used in the DMD measurement in ps (the detected pulse launched to the fibre), and X is a 'threshold' that is larger than 4.

For a 50 µm core GI multimode fibre with an NA = 0.200, one can approximate $\Delta\tau$ as follows:

$$\Delta\tau(\lambda,\alpha) = P_{00} + P_{10}\cdot\lambda + P_{01}\cdot\alpha + P_{11}\cdot\lambda\cdot\alpha + P_{02}\cdot\alpha^2$$

The constants P_{xy} are computed using a simulation model (Gholami, 2011), the result is shown in Figure 3a. Figure 3b shows the pulses leaving the fibre, referring also to Figure 1. When α = 1.6 → $\Delta\tau$ = 0.36 ps/m, so the delay between 2 mode groups after 550 m fibre is 200 ps.

The total power of all mode groups leaving the fibre depends on the launch radial offset. While approaching the edge (25 µm) of the core, the power will go down (some pulse energy is launched in the cladding, and power is lost because of core-cladding interface artefacts and slight fibre bending). The distribution of the power over the core radius depends also on the length of the fibre.

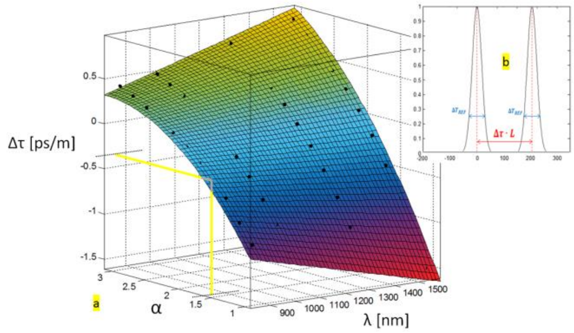

Figure 3: (a) 3-D plot showing which α suits best for the mode separating fibre (α = 1.6), used at a specific wavelength, to reach a clear separation of the mode groups after travelling through the fibre (b).

Figure 4 shows the theoretical power distribution over a Graded Index 50 µm core fibre. From now on referred to as 'Shape'.

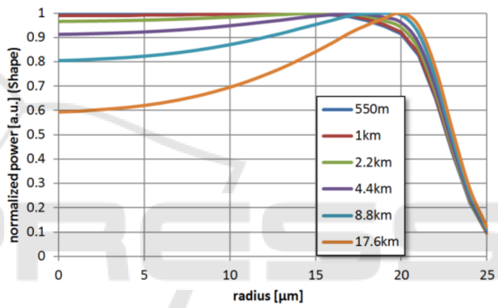

Figure 4: Theoretical power distribution ('Shape') over a Graded Index 50 µm core fibre. The distribution changes with fibre length.

Note: the shape of the trace shows a 'dip' in the centre as the fibre gets longer. This is because of the higher Ge content near the centre of the core, so attenuation increases faster with length for light travelling through the centre region of the core.

The mode separating fibre is a useful tool to characterize a detector on selective mode detection, to verify whether the detector is suited to qualify OM4 fibre; detect DMD profiles with maximum accuracy.

4 THE DETECTORS

According to the DMD measurement standard (TIA, 2003, IEC, 2017), the detected launch pulse should have a FWQM below a certain value. This value (ΔT_{pulse}) depends a.o. on the spectral width of the laser ($\delta\lambda$), the chromatic dispersion of the fibre ($D(\lambda)$) and the length of the fibre. The lowest DMD

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values to be measured with sufficient accuracy depends on ΔT_{pulse}. For OM4 fibre the specification is 0.10 ps/m. Figure 5 shows the relation between fibre length and the minimum required value for ΔT_{pulse} (for the used laser and fibre: $\delta\lambda$ = 0.1 nm, D(λ)= 95 ps/nm.km). The experiments are done on the mode separating fibre with a length of 550 m.

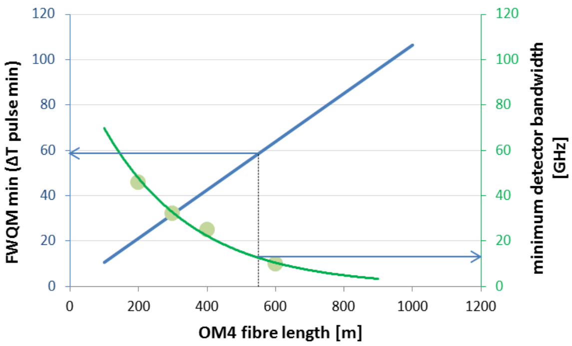


Figure 5: laser pulse and detector requirements to qualify OM4 fibre at different lengths.

A total of five commercially available detectors is studied. It is not the intention to review these detectors, and promote the best performing detector. The intention is to review commercial availability of very high speed multimode detectors that are mandatory for OM4 fibre qualifications when short fibre length are measured. For instance 400 meter, the maximum system length. The five detectors are all commercially available (high speed optical electrical converters, fibre coupled, some less easy to find), and will be left anonymous. The exact internal structure of some of these detectors is unknown.

nr	Specified range [nm]	Responsivity A/W @ 850 [nm]	Specified Optical Bandwidth [MHz.km]	Internal fibre pigtail
1	700-1650	?	10	62.5 µm '?'
2	700-1650	0.59	20	62.5 µm 'tapered'
3	400-870	0.08	45	50 µm 'direct'
4	700-890	0.4	30	50 µm '?'
5	800-1650	0.48	25	62.5 µm 'tapered'

Detector #1 is an integrated optical-electrical module (responsivity in A/W is not specified). The detectors #2 and #5 use an internal tapered pigtail; the sensitive detection area is near 30 µm diameter. Detector #3 is special because it is very fast (45 GHz), despite using a 'direct' coupling of the 50 µm internal pigtail to the sensitive detection area (without internal fibre lensing or tapering). The relatively large area must be thin to reach the high detection speed, and as a consequence the responsivity is very low (Hui, 2012).

For instance, from Figure 5, it shows detector #1 is too slow (10 GHz), case an OM4 fibre is measured at maximum system length (400 m), the specified detector bandwidth should then at least be 20-25 GHz. Only four of such detectors (multimode, ≥ 20 GHz) are commercially available to date and to our knowledge.

5 MEASUREMENT RESULTS

5.1 Reference

First objective is to verify the theoretical Shape using 550 m of the α = 1.6 test fibre. The only way to verify this is using an optical detector with an homogeneous sensitive area significantly larger than the modes field diameter of the light leaving the α = 1.6 fibre. The output of the fibre must be radiated directly on the sensitive area of the detector, no optics (or fibre) in between. This measurement is done by performing a 'DMD scan' in 4 directions (4-Quadrant scan: 4Q). The way to do this is well described in the standardization documents (TIA, 2003, IEC, 2017). The laser source we use is a 10 ps Titanium Sapphire Picosecond laser. The 4Q scan enables accurate alignment of the fibre, so the launch at 0 µm radial position indeed is at the optical centre of the fibre. After the DMD scan, the 4 quadrants are combined, for instance by folding the pulses at each launch radius. The pulses leaving the fibre normally go to the high speed detectors under test, connected to a sampling module and signal analyser. However the large area detector is too slow to follow the fast Ti:Sapp laser pulses, so the incoming beam is modulated with a chopper at 160 Hz, connected to a Lock In Amplifier. At each radial launch position the signal is measured. Finally the 4 quadrants are averaged, resulting in the results shown in Figure 6.

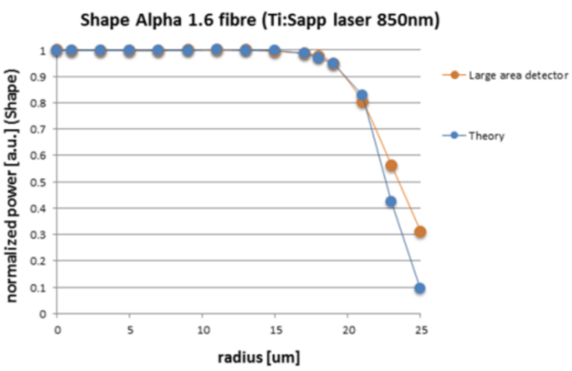
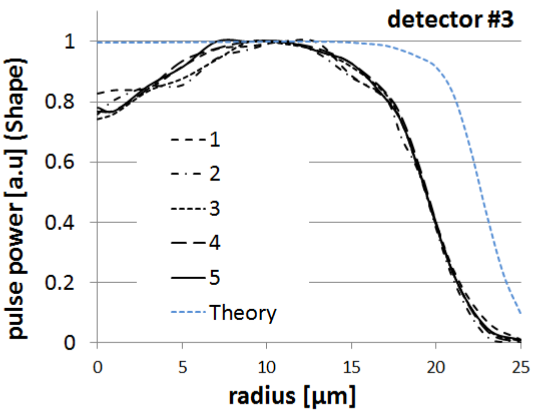
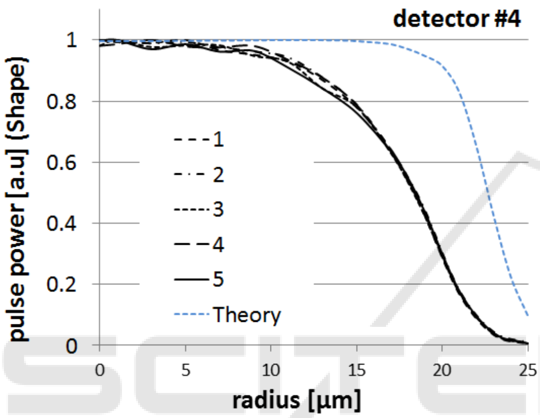


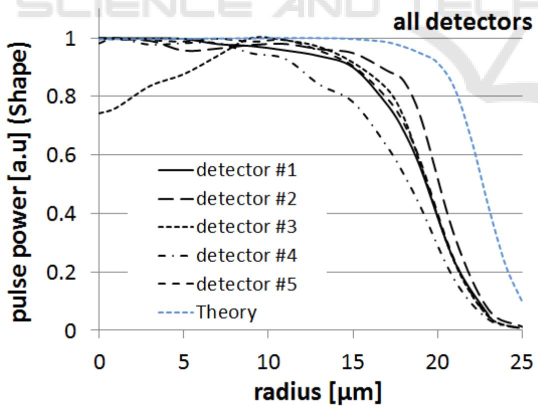
Figure 6: theoretical and verified 'DC 'power distribution (Shape) after 550 m α = 1.6 fibre.



(a)



(b)



(c)

Figure 7: (a) reproducibility of detectors #3 and #4. (b) Shape of all five detectors.

At the outer launch positions (23 & 25 µm from the centre), the experiment shows higher power, we believe this difference is caused by inaccuracies in the fibre index profile close to the cladding (scattering, leaky modes). Up to 23 µm theory and experiment are almost in accordance.

5.2 Detectors under Test

The coupling of laser pulses into the α = 1.6 fibre is realized by a direct coupling of a HP780 launch fibre (single mode at 850 nm, launch spot diameter 5 µm) to the α = 1.6 fibre. For both fibres, the cleave quality is checked by an interferometric technique, and is far below an angle of 1 degree (to avoid angular coupling to the α = 1.6 fibre). The 4Q DMD scan (including alignment, 850 nm) is executed five times per detector to visualize the reproducibility of the measurement. For detectors #3 and #4 the five power distributions ('Shapes') are shown in Figure 7a. The responsivity of detector #3 is very low, causing this detector to have the poorest reproducibility. Figure 7b shows the power traces (Shape) of all five detectors.

It is clear that none of these detectors reach the theoretical Shape. Since the exact internal structure of the detectors in unknown, it is hard to explain the observed differences.

5.3 Discussion

The internal fibre pigtails of detectors #2 and #5 are 'tapered'. So the pigtail output field to the detector sensitive area is reduced to a smaller area (from 62.5 to 30 µm diameter). In some way modes are lost, and do not reach the sensitive area (or reach the area, but do not generate current). It makes sense the lost modes are the modes that travel closest to the cladding. The Shape for both detectors is nearly equal, detector 2 is slightly closer to the theoretical Shape (detector 2 has a slightly lower bandwidth, so maybe the sensitive area is just a little larger).

Detector #1 shows a Shape equivalent to #2 and #5, which might mean it is also equipped with an internal tapered (or lensed) fibre pigtail.

Detector #3 is the oddball of the selection. It has an internal 50 µm pigtail that is not tapered or lensed, and -as a consequence-, uses a larger and thinner sensitive area. So it causes a significantly lower responsivity (Hui, 2012). Still, the Shape does not reach theory. For the outer part (narrow shape) two explanations might be considered: bend losses of the internal pigtail (50 µm shows more bend loss compared to 62.5 µm), as the pigtail is bended over few cm inside the detector housing. We also noticed a poor coupling of the pigtail to the sensitive area (slight mismatch). An interesting solution might be to use 'bend-insensitive' 50 µm fibre as the internal pigtail. The 'dip' in the middle is more difficult to explain. Possibly the homogeneity of the sensitive detector area is poor because it needs to be thin to reach the high speed (45 GHz).

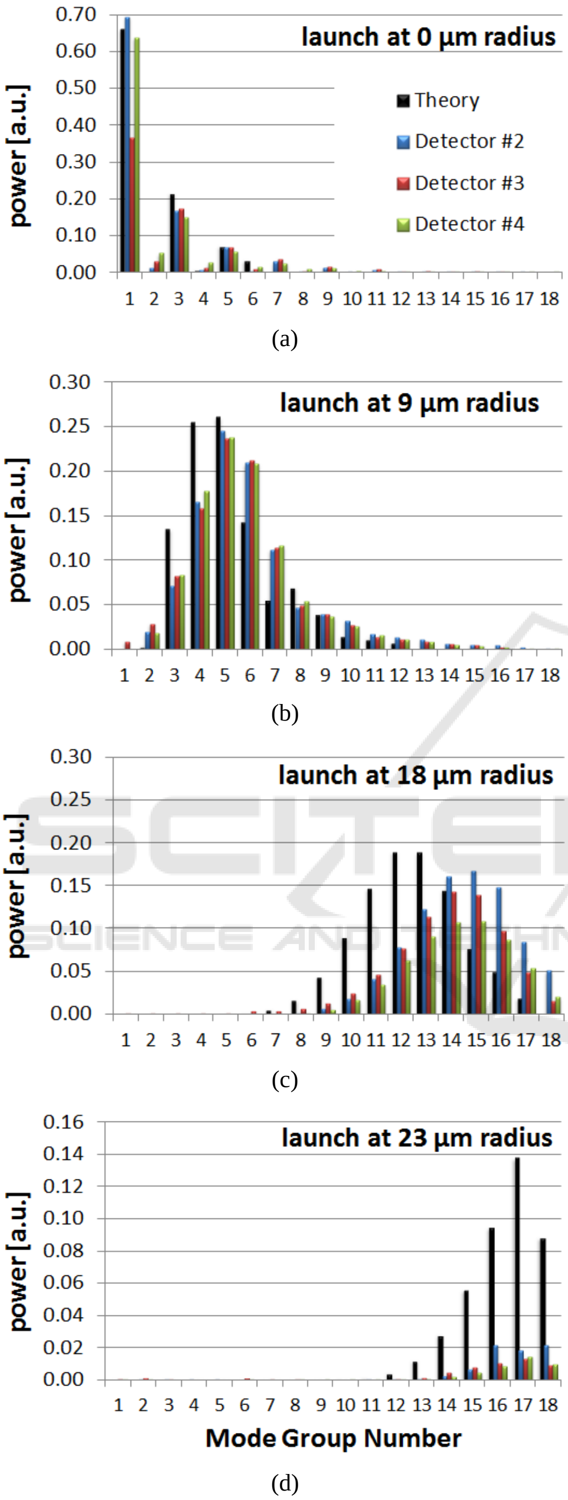


Figure 8: Detected mode group powers of the #3 detectors considered at launch radii of 0 µm (centre), 9 µm (most mode groups detected), 18 µm (relevant for 'inner' DMD), and 23 µm ('outer' DMD).

Finally detector #4. The Shape is 'roundish'. The size of this detector is very small, and it is completely sealed. The internal structure is unknown. This detector proves to be the least suited to qualify OM4 fibre; it shows the narrowest shape of all five detectors.

5.4 A Closer Look

The previous results will show as well by using a regular OM4 fibre rather than the α = 1.6 fibre; the differences in Shape are almost equivalent. Using the α = 1.6 fibre however generates the ability to verify the detector response not only per launch offset radius, but also per mode group. To simplify analysis, we consider detectors #2 (widest Shape), #3 (centre dip) and #4 (narrowest Shape).

In Figure 8 the detected powers per mode group at 4 launch offset radii are plotted together with theoretical values derived from the simulated DMD profiles (detector #2 shown in Figure 2a).

To scale the power levels equal, it is assumed at 9 µm radial offset, all mode groups are detected. From Figure 2 it shows the agreement between the simulated and measured DMD profile (detector #2) is fair, however when approaching the cladding, the differences increase. This is probably caused by core-cladding interface artefacts of the α = 1.6 fibre. Further, to optimize the model, one must know the exact Alpha value, core-size and Delta (Oh, 2012), and these must be very constant over full length (550 m) of the α = 1.6 fibre (here's another challenge).

From Figure 8a, theory, 'odd' mode groups are symmetric whereas 'even' mode groups are anti-symmetric (Gholami, 2011). So no power at fibre output by the even mode groups. This is well confirmed by the experimental data.

Detector #3 fails to detect full power of the first mode group, while the third and fifth mode group approach theory. Probably caused by an artefact in the centre of the detector sensitive area, which is a reason to reject detector #3 for OM4 fibre qualification.

Figure 8b and 8c show a typical but unexpected result. The measured mode group power distributions of the three detectors shift to higher order modes compared to theory. One might expect the opposite as higher mode groups are more sensitive to selective mode detection. We expect this is caused by local imperfections of the index profile of the mode separating fibre (α = 1.6 fibre, figure 1). This observation needs further research.

Figure 8d, when launching close to the cladding, it clearly shows the loss of power for all three

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detectors compared to theory. Main cause of the narrow experimental Shapes shown in Figure 7b.

6 CONCLUSIONS

To date, to our knowledge, no commercial available high speed detector (≥ 20 GHz) exists that can detect all modes leaving the OM4 fibre under test.

We made a specially designed 'mode separating fibre', and we used this fibre to characterize performance of five commercially available high speed detectors. The method clearly shows the limitations of these detectors to qualify OM4 fibre. Which does not mean these fibres will fail in systems, it just shows the ideal detector for qualifying OM4 fibre is not yet commercially available. The next challenge is to explain the observed mode selective detection by considering the internal structure of these detectors in detail. Another challenge is to bring simulated and measured data closer by improving the quality (accuracy of index profile and homogeneity over length) of the mode separating fibre. From there improvement to the detector design may lead to the 'perfect' detector for purpose of OM4 fibre qualification. A first improvement to the internal structure of the detector might be to use a 'bend-insensitive' Graded Index multimode fibre to serve as internal pigtail. This will cause less modes to leave the pigtail from the side.

ACKNOWLEDGEMENTS

The authors would like to thank J.G.A. Achten, retired teacher technical English, for reviewing this paper.

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