Accurate calibration of S^2 and interferometry based multimode fiber characterization techniques

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Abstract: We present a novel method to validate the relative amount of power carried by high order modes in a multimode fiber using a Spatial and Spectral (S^2) imaging technique. The method can be utilized to calibrate the S^2 set-up and uses Fresnel reflections from a thin glass plate to compare theoretical values with experimental results. We have found that, in the most general case, spectral leakage and sampling errors can lead S^2 to underestimate the multipath interference (MPI) of high order modes by several decibels, thus significantly impairing the result of the measurement. On the other hand, by applying suitable corrections as described in this work, we demonstrate that the S^2 produces MPI estimates that are accurate to within 1dB or better.

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OCIS codes: (060.0060) Fiber optics and optical communications; (060.2270) Fiber characterization; (030.4070) Modes; (060.4005) Microstructured fibers.

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Spectral (S²) imaging technique, originally developed by Nicholson et al. [11], is the most powerful and sensitive. In order to acquire modal information on the fiber, these methods measure the interference that arises from the different group velocity of the various optical modes. Several variants have been proposed, in which the interference is probed in the frequency domain [5–7], time domain [8,9], or in the spatial domain [10]. The Spatial and Spectral (S²) imaging technique, originally developed by Nicholson et al. [11], is the most widely used approach. It differs from most of the others as it does not require any prior knowledge about the refractive index profile, guidance mechanism or modal properties of the fiber under test (FUT). It can detect very small fractions of power present in higher order modes (HOMs), up to 50-60 dB below the fundamental mode (FM). For each HOM, the S² provides the relative intensity compared to the dominant mode launched inside the same fiber (typically - but not necessarily - the FM). This is referred to as the multipath interference (MPI = 10log₁₀(I_HOM/I_FM)). Moreover, it produces information about differential group delay.

1. Introduction

Few mode and multimode fibers have recently undergone a surge of renewed interest for applications in telecommunications and high-power fiber lasers and amplifiers; where space division multiplexing (SDM) can provide a way to increase the information capacity of a single fiber and the large modal area of these fibers is beneficial in alleviating detrimental nonlinear effects and reducing the chance of fiber damage, respectively. The development of reliable and accurate techniques to investigate in detail the modal content of multimode fibers has thus become a topic of great interest. In recent years many techniques have been developed to measure the modal content of few mode fibers, for example based on selective mode launch [1,2], modal weight solvers [3] and time of flight [4]. Those techniques based on interferometry are arguably amongst the most powerful and sensitive. In order to acquire modal information on the fiber, these methods measure the interference that arises from the different group velocity of the various optical modes. Several variants have been proposed, in which the interference is probed in the frequency domain [5–7], time domain [8,9], or in the spatial domain [10].
(DGD), the spatial phase and the intensity profile of all the optical modes it detects. Since its first demonstration, a number of improvements have been proposed, aimed at making the $S^2$ technique faster, more accurate, more sensitive and better suited for a wider variety of characterization problems. For instance, a substantial reduction in measurement time and signal-to-noise ratio was obtained by modifying the original approach. This was based on a broadband light source and a scanning fiber probe with a spectrum analyzer at the output of the FUT [11]; this was replaced by a tunable laser source (TLS) and a charge coupled device (CCD) [12]. Improvements in the data processing algorithms have allowed removal of the requirement of a dominant fundamental mode [13,14] and removal of spurious modal interference peaks [15,16]. However, these improvements have only been theoretically validated. While the accuracy of the $S^2$ technique in measuring DGD has been quantified, e.g. through comparison with simulation predictions, its accuracy in determining the correct MPI of all modes has not yet been investigated in detail; only one approximate validation experiment has been reported so far using a long period grating (LPG) to produce a well-defined amount of power in a higher order mode. However, this approach involves writing a long period grating in the FUT [11], which adds complexity and is in general undesirable. In this earlier work the MPI measured for a HOM is validated by comparing it with the attenuation at the resonant frequency of the LPG followed by a suitable HOM stripper. This method works best with thermally inscribed LPGs [17], but is rather cumbersome as it requires optimization of the LPG inscription and the HOM suppression procedure, which is dependent on the particular HOM and the FUT.

In this paper we propose and implement a simpler and more versatile method to accurately calibrate the MPI values measured via $S^2$. While working on the validation of this method we have also identified two potential sources of substantial error in the reconstructed MPI values. These originate in the data collection and processing and are due to sampling errors and spectral leakage. Whilst they are well known effects in digital signal processing, they had not been previously considered in the context of $S^2$ measurements. In this work we quantify their impact and identify strategies to minimize them. Finally, we apply the findings to the analysis of a 19-cell Hollow Core Photonic Bandgap Fiber (HC-PBGF), characterizing its modal content and discussing in detail the impact of the corrections identified for each mode.

2. Independent validation and calibration of MPI values

In order to make a meaningful comparison between different modal characterization techniques, a suitable benchmark needs to be developed that allows the accuracy of the measured modal powers to be established. Here we follow a simple, direct and robust approach to achieve a modal calibration that does not require any grating fabrication. We exploit multiple Fresnel reflections from a suitable optical element positioned within the measurement beam path, to compare experimental results with well-defined theoretical MPI and DGD values.

The technique originated from the observation of spurious interference peaks in $S^2$ spectra obtained via a TLS and CCD set-up, which highlighted the problem of multiple reflections from optical elements present in the optical path [16]. If an optical element of known material
and dimensions is used, the position and power of the generated double reflection peak can be easily calculated from well-known Fresnel Eqs.; furthermore, such a peak structure can be used to calibrate the measurement. Assuming transmission from a dielectric with refractive index $n(\lambda)$ to air, refractive index $n = 1$, the Fresnel reflection ($R$) and transmission ($T$) coefficients, orthogonal (⊥) or parallel (∥) to the incident plane of polarization, are given by [18]:

$$R_{⊥}(n,\theta_{\text{dielectric,air}}) = \left(\frac{n \cos(\theta_{\text{dielectric}}) - \cos(\theta_{\text{air}})}{n \cos(\theta_{\text{dielectric}}) + \cos(\theta_{\text{air}})} \right)^2,$$

$$R_{∥}(n,\theta_{\text{dielectric,air}}) = \left(\frac{\cos(\theta_{\text{dielectric}}) - n \cos(\theta_{\text{air}})}{\cos(\theta_{\text{dielectric}}) + n \cos(\theta_{\text{air}})} \right)^2,$$

$$T_{⊥∥}(n,\theta_{\text{dielectric,air}}) = 1 - R_{⊥∥}(n,\theta_{\text{dielectric,air}})$$

where $\theta_{\text{dielectric,air}}$ is the angle of the light ray, in air and the dielectric, to the perpendicular of the air-dielectric interface; $\theta_{\text{air}}$ is given by the angle of the optical element to the beam propagation, Fig. 2., and $\theta_{\text{dielectric}}$ is obtained with Snell’s law. If a dielectric slide is inserted in the optical path a fraction of the optical beam will undergo a weak double reflection, furthermore, very weak multiple double reflections could also be produced. However, these can be neglected as they do not interfere with the first doubled reflected beam. The first double reflected beam acts as a virtual ‘HOM’: it propagates parallel to the primary beam and its power and delay can be easily calculated from Eqs. (1) and (2). Figure 2(b) shows a schematic of a ray propagating through a dielectric window tilted at a moderate (20°) angle to help visualization.

The DGD, induced by the optical element, between the transmitted ‘FM’ and the double reflection ‘virtual HOM’ is the time difference between when they split (point A) and when they arrive at a point belonging to an equi-phase front after the glass plate, e.g., points D and C in Fig. 2(b). Therefore, $\text{DGD} = t_{AB} + t_{BC}-t_{AD}$, which after some trivial algebra can be written as,

$$\text{DGD}(n(\lambda),\theta_{\text{air}}) = \frac{2\tau(\lambda)-2\tau \sin^2(\theta_{\text{air}})}{c \cos(\arcsin(\sin(\theta_{\text{air}})/n(\lambda)))},$$

It can also be seen that for $\theta \neq 0$ a spatial offset exists (i.e., the length DC) between the lateral position of the ‘FM’ and the ‘HOM’. This will cause the modes to have a reduced spatial
overlap, thereby reducing the measured MPI value. This feature, which obviously does not physically manifest itself in a normal S² measurement, introduces a small error that can be estimated by the difference between two theoretical MPI values, one with and one without the additional lateral offset of the FM and HOM. This can usually be disregarded for small to moderate angles (e.g., <0.09dB at <20° for a 4mm thick plate with n = 1.74).

By applying the Fresnel formulae for R and T at the optical interfaces, Eqs. (1)-(3), and by varying θ_{air} and n(λ), the polarization dependent intensity of the FM and “virtual” HOM can be obtained: D_{⊥,||}(n(λ), θ_{air}) = T_{⊥,||}(n(λ), θ_{air}) and C_{⊥,||}(n(λ), θ_{air}) = R_{⊥,||}^2(n(λ), θ_{air}), respectively. Therefore, the theoretical MPI due to Fresnel reflections is MPI_{⊥,||}(n(λ), θ_{air}) = 10\log_{10}(C_{⊥,||}(n(λ), θ_{air})/ D_{⊥,||}(n(λ), θ_{air})), giving:

\[ \text{MPI}_{⊥,||}(n(λ), θ_{air}) = 10\log_{10}(R_{⊥,||}^2(n(λ), θ_{air})) \] (5)

This is plotted in Fig. 3 for glass plates of different refractive indices and angles of incidence.

![Fig. 3. Ideal theoretical Fresnel based MPI values for a “virtual” HOM as a function of angle of incidence (a) parallel (b) perpendicular incident polarization](image)

The MPI value, and also the DGD value, corresponding to the double Fresnel reflection depend in general on the refractive index and thickness of the plate, angle of incidence and polarization of the incident light, thus the slide provides an ideal independent metric to calibrate the accuracy of any S² system over a broad range of MPI and DGD values.

3. Measuring a ‘virtual’ higher order mode

S² measures the variation of spatial intensity over wavelength of the magnified near field fiber output [11]. In a two mode fiber, this is given by:

\[ I(x, y, ω) = A_{FM}(x, y, ω)^2 + A_{HOM}(x, y, ω)^2 + 2A_{FM}(x, y, ω)A_{HOM}(x, y, ω)\exp\left(\left(\beta_{FM}(ω) - \beta_{HOM}(ω)\right)L + Δφ\right), \] (6)

where \(A_{i}(x, y, ω)\) are the spatial and frequency dependent modal amplitudes, \(Δφ\) is the intermodal phase difference and \(β_{i}(ω)\) are the frequency dependent modal propagation constants. For each spatial point (pixel), the measured variation of the received signal with wavelength is converted to frequency and then Fourier transformed to the time domain, where the amplitude and temporal difference between the FM and the HOM peaks are measured to calculate the MPI values of the modal combination at the receiver and the DGD of the fiber. In addition, data post-processing also allows reconstruction of the intensity distribution of the FM and HOMs, as well as the relative spatial phase difference between the two.

The experimental set-up we use to demonstrate the method uses a scanning tunable laser source (Agilent, 81940A) and an InGaAs CCD camera (Xenics, Xeva-1.7-320), see Fig. 4. The TLS has a linewidth of 0.8fm and is scanned at a constant speed of 500pm/s; the CCD

#234369 - S15.00 USD  Received 11 Feb 2015; revised 5 Apr 2015; accepted 9 Apr 2015; published 15 Apr 2015  © 2015 OSA  20 Apr 2015 | Vol. 23, No. 8 | DOI:10.1364/OE.23.010540 | OPTICS EXPRESS 10544
has a 500 Hz frame rate and a 1ms integration time, which determines an effective laser linewidth of 0.5pm.

The measured MPI values are collected using the apparatus shown in Fig. 4. We used a single mode fiber and interposed in its collimated output beam, between the polarizing optics and the CCD camera, a sapphire window (Crystran) of known thickness (4 mm ± 0.1) and refractive index \( n \sim 1.743 \). This optical element was chosen so that the MPI value of the double reflection would not infringe the dominant FM mode requirement of \( S^2 \) and the DGD peak would be clear of additional spurious peaks due to reflections from flat optical elements in the camera, as identified in earlier measurements [18]. The sapphire window was mounted on a rotational stage and initially aligned perpendicular to the propagation direction of the beam. We collected a set of angle resolved measurements over the 1550-1554 nm bandwidth, using a 10 pm resolution, at orthogonal angles of incident polarization, as the sapphire window was tilted from \(-20^\circ\) to \(20^\circ\) at \(1^\circ\) intervals.

![Fig. 4. Schematic of the modified \( S^2 \) setup to measure the MPI value from the double reflection of a sapphire window.](image)

Figure 5(a) shows an example of one \( S^2 \) measurement. The value of the peak at around 50 ps delay (green point) corresponds to the measured MPI. In blue we show, in the same plot, the theoretical value (i.e. DGD and MPI values extracted from Eqs. (4) and (5)). A comparison between measurements and theoretical predictions is shown in Figs. 5(b) and 5(c) for an incident polarization parallel and perpendicular to the axis of rotation of the sapphire window, respectively.

![Fig. 5. DGD graph of the double reflection “virtual” HOM generated by a 3mm thick sapphire (a). Comparison between theoretical and experimental MPI values for the “virtual” HOM, as a function of angle of incidence, (b) parallel (c) perpendicular incident polarization](image)

As shown in Figs. 5(b) and 5(c), and as found in all other measurements, the MPI value measured at the peak point of the HOM modal interference was systematically lower than the theoretical value from Eq. (5). This often large oscillation in the MPI error value as a function...
of angle was observed in all measurements we made. Given the magnitude and systematic nature of this error, we performed a thorough analysis to determine its cause, which is presented in the next section.

4. Sampling error and spectral leakage

The S² algorithm samples and Fourier transforms an analog signal, i.e. the light intensity in one spatial pixel at the receiver, modulated by the beating between all the modes. Both these operations may introduce errors.

Amongst the different types of Fourier transforms available, the fastest and most widely used is the FFT. In order to generate the desired Fourier transformed signal in the time domain, the samples need to be equally spaced in the frequency domain. With most acquisition techniques, however, evenly spaced data in wavelength, rather than frequency, are more typically obtained. Therefore, a conversion of equi-spaced wavelengths into equi-spaced frequency samples is required. While it is in principle possible to perform such conversion without introducing any significant errors [19,20], for example through use of an ideal sinc interpolation filter, this ideal reconstruction is not realistic due to the need for the sinc function to extend from $-\infty$ to $\infty$, which is not possible for practical band-limited signals. A more suitable alternative is through the use of a polynomial spline interpolation [21], which effectively resamples and applies a low pass filter to the signal. This has the result of attenuating the higher DGD components and it is what we refer to here as the sampling error.

Besides the sampling error, in all Fourier transform based systems another known effect called spectral leakage can introduce additional errors [22], where the peak power, in the Fourier domain, is reduced and is transferred to the adjacent sampled points, Fig. 6(f) black arrows. Spectral leakage occurs whenever the necessarily finite portion of the signal under test does not contain an integer number of signal periods. This generally causes the peak amplitude of the Fourier transformed signal (hence in our case the peak MPI value) to be reduced. Mathematically, the signal under test can be seen as the multiplication of the continuous signal extending between $-\infty$ and $\infty$ with a top hat function that limits its extension to the measurement time only, therefore producing a band-limited signal Fig. 6(c). In the Fourier domain this equates to a convolution between the original signal’s spectrum (e.g. a Dirac delta peak for a single sinusoidal signal, centered at the signal frequency, Fourier position (Fp) in Fig. 6(b)) with a sinc function. This produces a sinc function centered on the Fourier position of the signal, as shown in Fig. 6(d). This sinc function is then sampled at regular intervals, otherwise known as the picket fence effect, Fig. 6(e). Unless the top hat duration is a multiple of the signal period, a peak with reduced height and increased width is observed, This phenomenon produces some uncertainty in the position of the peak (DGD error) and, most importantly, an error in the MPI value (shown in Fig. 6(f) black arrows), also known as scalloping loss, that can be shown mathematically to be up to a maximum of 3.92 dB [23].
Fig. 6. An illustration of spectral leakage; (a) A pure sine wave and top hat function, (b) processed with an FFT to produce a delta and sinc function respectively. (c) Multiplication of the sine and top hat function produces a band-limited function. (d) The FFT is a sinc function centered at delta function Fourier position (FP). (e) The band-limited function is picket fenced producing (f) the FFT of the sampled sine wave. Spectral leakage, (f) black arrows, occurs when the sampled sin wave does not contain an integer number of periods.

In a typical S² measurement case, the modal waveform is constructed of an unknown number of modes, each one with unknown DGD. Therefore, it is impossible to choose measurement parameters that would eliminate spectral leakage from occurring completely from the majority of results; it is thus paramount to develop a suitable numerical correction, as detailed below.

5. Modeling sampling error and spectral leakage

The effect that spectral leakage and sampling error have on the MPI value of the S² based systems has been analyzed numerically. We accurately modeled these errors by generating a “reference” S² signal corresponding to an idealized fiber having a single HOM with a fixed MPI and a known DGD, Eq. (6) [24]. By varying the DGD of this simulated signal at a constant MPI (set at −23 dB in this case), we were able to investigate the amplitude fluctuation of both spectral leakage and sampling errors, see Fig. 7(a) (note that the DGD has been normalized by the Nyquist sampling frequency). The blue points show the difference between the calculated and the theoretical MPI value. The sampling error, shown by the green symbols, was found to increase monotonically as the DGD value approaches the Nyquist sampling frequency. The spectral leakage error depends on the particular value of DGD relative to the total spectral width of the measurement. As seen in the plot, it oscillates between 0 and the maximum theoretical value of 3.9 dB, in good agreement with expectation. The red symbols show a worst-case scenario where sampling and maximum spectral leakage errors occur simultaneously.

A well-known digital signal processing technique to minimize spectral leakage is to consider the contribution of additional sampled points in the resulting sinc adjacent to the one closest to the peak position [22]. For example, Fig. 7(b) shows that by computing the MPI as a sum (on a linear scale) of 3 points at either side of the experimental peak value, the maximum spectral error can be reduced from ~3.9 dB to ~0.3 dB.
This error can be reduced further by summing more points (if they exist) belonging to the same peak, although we have found empirically that 3 points on either side of the peak is generally a good compromise.

To minimize the sampling error one can either reduce the spectral bandwidth of the measurement or introduce a suitable, pre-calculated, correction factor. Figure 7(b) shows that for the first scenario: if the measurement bandwidth is reduced from 6 to 2 nm at a constant 10 pm resolution, the maximum error can decrease from 7dB (purple trace) to <1dB (blue trace).

![Fig. 7. (a) Analysis of spectral leakage and sampling errors vs. DGD for a given set of experimental conditions (1550-1557 nm bandwidth, 10 pm resolution), showing the sampling error increasing with DGD and the spectral leakage (SL) error oscillating between 0 and ~3.9dB. (b) Strategies to minimize errors: SL is reduced to ~0.3 dB by estimating the MPI as sum of 3 points at either side of the peak value; the sampling error can be reduced to <1 dB by reducing the measurement bandwidth (to ≤3 nm in this particular instance).](image)

It is however not always possible or advisable to reduce the spectral bandwidth of an S\(^2\) measurement, due to the modal complexity of the FUT or because a high DGD resolution is required. In these cases a sampling error is unavoidable. Figure 8 provides a comprehensive description of the sampling error in the general case. Here, the sampling error (in dB) is plotted as a function of the DGD (abscissa, again normalized to the Nyquist sampling frequency) and of a normalized bandwidth, which allows “universal” correction factors to be obtained.

![Fig. 8. Plot showing how the MPI is underestimated due to sampling error. The latter is plotted as a function of the DGD normalized to the Nyquist frequency (abscissa) and to a normalized bandwidth, which allows “universal” correction factors to be obtained.](image)
points). With this choice of normalization, the resulting plot is valid for any number of points, bandwidth and choice of the central wavelength. The Fig. shows that the sampling error is always small (<1dB) for normalized DGD values below ~0.7 (i.e. DGD ~70% of the Nyquist frequency), irrespective of the choice of measurement bandwidth and number of sample points. On the other hand, if the normalized bandwidth value is lower than 0.82, the sampling error is also <1dB; this situation corresponds to the blue curve in Fig. 7(b). However, in the general case of high resolution data sets, the latter condition is found not to be satisfied, the MPI is underestimated by over 1dB and a suitable correction factor must be applied. Although Fig. 8 was obtained by assuming a fixed maximum MPI value of −23dB, we have verified that the results are virtually independent of the MPI - and thus Fig. 8 can be utilized to infer the correction factor in the most general case. Figure 9 shows how the various error components vary as a function of the MPI value (−23dB in the cases described in both Figs. 7 and 8), demonstrating that the contributions are constant with the MPI as long as the “dominant mode approximation” [24] holds, i.e MPI≤10dB. On the other hand, it should also be observed that absolute errors will vary if a different type of interpolation and window filter are used as compared to the spline interpolation and box filter used here. In this case, it is possible to follow the procedure and guidelines presented here to obtain suitable correction maps (similar to that in Fig. 8) tailored for the particular choice of procedure for data analysis.

Fig. 9. Dependence of the various MPI error components, including sampling error and spectral leakage, on the absolute value of the MPI, showing virtually no dependence as long as there is a dominant FM relative to a single HOM [11].

6. Validation of the MPI values

Here we show how, by using the previously discussed spectral leakage and sampling error minimization methods, the S² technique can be validated and calibrated with fairly high accuracy by using the 'virtual' HOM generated by the double reflection of a dielectric window. We use the experimental results shown in Fig. 5; first we reduce spectral leakage by summing in linear scale all the sampled points belonging to the HOM interference peak (green dots in Fig. 10(a)) which lie above the measurement noise floor. Secondly, we minimize the sampling error by applying the appropriate correction factor from Fig. 8 with appropriate scaling for the summed MPI value. As shown in Figs. 10(b) and 10(c) the corrected MPI values now fall very close to the expected theoretical values.
Fig. 10. (a) DGD graph of the measured sapphire window double reflection modal interference peak summed MPI value. Comparison between theoretical and experimental MPI values for a “virtual” HOM generated by the sapphire window, as a function of angle of incidence, (b) parallel (c) perpendicular incident polarization.

Figure 11 shows a summary of results for the two incident polarizations, demonstrating that <1dB MPI error can be achieved in both cases. There is, however, a small discrepancy in the corrected results, which can be explained by the fact that the sapphire window had an unknown orientation of its slightly birefringent crystal axis, \( n_o = 1.7462 \) and \( n_e = 1.7384 \) at 1550nm [25]. This result shows that the S² method, if appropriately calibrated, can provide accurate MPI readings, and that the Fresnel double reflections from planar optical elements can be used to validate the set-up.

Fig. 11. Residual MPI error (both polarizations) after spectral leakage and sampling error corrections.

7. Measurement of a HC-PBGF

To conclude this work, we have investigated the effect of spectral leakage and sampling errors on a typical, real S² measurement. We have chosen a 19-cell hollow core photonic band gap fiber (HC-PBGF) that has been already extensively studied [4]. The fiber has a minimum loss of 3.5 dB/km at ~1500 nm and a very wide, surface mode free central region of the
bandgap with a 3-dB transmission bandwidth of 160 nm [26]. The $S^2$ measurement was performed over a 9.8m long sample of fiber with the system described in Section 3, using a 1550-1555 nm bandwidth and a 10 pm resolution, which gives a maximum DGD value of 41 ps/m. Light from the TLS source was butt-coupled into the HC-PBGF from a single mode fiber, with a slight offset to enhance the modal content. The results are plotted in Fig. 12, showing the peaks and intensity distributions corresponding to the main optical modes of the HC-PBGF.

In Fig. 13 we plot the estimated errors due to sampling and spectral leakage calculated using the procedure detailed in Sec. 5. The error due to spectral leakage is found to oscillate between 0 and ~4dB, in good agreement with theory, and similarly the sampling error is found to monotonically increase with increasing DGD. If these effects were not accounted for, the MPI value could be significantly underestimated by between 1.48dB to 9.3dB for this particular measurement, which shows the importance of calibrating the set-up and of using the corrections discussed in this work.

8. Conclusion

We have presented an experimentally simple and robust method that validates the accuracy of the $S^2$ technique in acquiring the relative amount of power (MPI) of high order modes. The technique could be used as a benchmark method to calibrate new $S^2$ set-ups or indeed many
other interferometric-based modal characterization techniques. The technique relies on the
creation of a “virtual” HOM with known DGD and MPI through the use of an optical element
(window) of known properties. A first experiment using this method has allowed us to
identify sampling and spectral leakage as potential sources of significant errors. We have
therefore studied and proposed effective strategies to minimize their effects, which we believe
should also affect other Fourier-transform based modal characterization systems.

Using these error calibration techniques we have finally assessed the impact of errors due
to sampling and spectral leakage in a typical few-moded fiber measurement. Furthermore, we
have shown that a combined error that leads to an underestimate of the MPI of some HOMs
of nearly 10 dB, which can be possible if appropriate precautions in the choice of
measurement parameters are not taken, and suitable correction factors are not applied.

Acknowledgments

This work was supported by the EU 7th Framework Programme under grant agreement
228033 (MODE-GAP) and by the UK EPSRC through grant EP/H02607X/1 (EPSRC Centre
for Advanced Manufacturing in Photonics). F. Poletti and D. J. Richardson kindly
acknowledge support from the Royal Society.