Recovery of highly-dispersive modes using a wavelength-resolved modified S^2 imaging method

Erick Lamilla,[1] Ivan Aldaya,[2] Maicon S. Faria,[1,3] Paulo F. Jarschel,[1]
Julián L. Pita,[4] and Paulo Dainese[1,*]

[1] *Institute of Physics "Gleb Wataghin," University of Campinas (UNICAMP), 13083-859, SP, Brazil*
[2] *Campus São João da Boa Vista, State University of São Paulo (UNESP), 13876-750, SP, Brazil*
[3] *National Center for High Performance Computing in São Paulo (CENAPAD-SP),13083-889, SP, Brazil*
[4] *School of Electrical and Computer Engineering, University of Campinas (UNICAMP), 13083-852, SP, Brazil*

[*] *dainese@ifi.unicamp.br*

Abstract: We present a modified wavelength-resolved S^2 method that allows recovery of highly-dispersive modes. We employed this method using a variable window spectrogram to characterize a hollow core photonic crystal fiber where several surface-modes are recovered.

OCIS codes: (060.2310) Fiber Optics; (060.4510) Optical Communication; (060.5295) Photonic crystal fibers.

Multi-mode optical waveguides are used in a wide range of applications. In mode-division multiplexed communication systems for instance, different modes are exploited to increase the aggregated capacity through mode division multiplexing [1]. In other scenarios, the presence of multiple modes may cause undesired effects. This is the case of hollow core (HC)-photonic crystal fiber (PCF), where different propagation modes result in multi-path interference and a wavelength-dependent beam shape [2]. Either if the multi-mode nature is a desirable feature, or if it constitutes a negative effect, characterizing modal content is critical, not only to understand the behavior of the system but also to improve future designs. The spatial and spectral S^2 imaging method has been successfully employed to characterize few mode fibers [3] as well as HC-PCFs [2]. This method is able to recover the mode profiles from the spatial and spectral interference between the dominant fundamental mode and higher-order modes. S^2 is simple and does not require any previous knowledge of modes' profile. In some scenarios, however, certain limitations have to be overcome. For example when the intensity overlap between the fundamental mode and other modes is relatively small or when highly dispersive modes are present. In particular, this is the case for surface modes (SMs), whose power is concentrated in the vicinity of the photonic crystal boundary [4] and, at certain specific wavelengths can couple to the fundamental mode, creating anti-crossing points. A combination of an external reference (such as proposed in [5]) and a wavelength resolved processing with variable window applied to the S^2 method would allow the mode recovery of this surface modes and understand their interaction with core-guided modes. In this paper, we apply a wavelength-resolved modified S^2 imaging method to recover highly dispersive modes excited in a waveguide, and show the results for a HC-PCF.

In order to recover the highly-dispersive modes of the HC-PCF under test, we implemented two modifications to the standard S^2 method. The first modification was the use of a fraction of the incoming laser power as an external reference in a Mach-Zehnder interferometer (MZI) configuration, as shown in Fig. 1(a). The light of a tunable laser is collimated by a lens and then divided using a polarization beam splitter (PBS). The light in one of the arms of the MZI is transmitted through a 0.98-m-long fiber sample and combined in a beam splitter (BS) with the reference wave coming from the other MZI arm. The combined beam is captured by an InGaAs camera, where the interference pattern between the reference and fiber modes is recorded, for wavelengths ranging from 1520 nm to 1640 nm in steps of 8 pm. Since the reference beam does not traverse the fiber, it is not affected by the high attenuation region of the fiber, in contrast to the standard S^2 method, where the fundamental mode used as a reference may not be dominant in high-attenuation regions [4]. Additionally, the reference beam spot size can be larger than the fiber modes, allowing the reference to overlap well beyond the core region and revolve spatially the SMs. The HC-PCF used in our experiment has a 7-cell core with an approximate diameter of 16 μm, a cladding pitch of 4.9 μm and an air-fill fraction of 92%, which were directly measured from the scanning-electron microscope (SEM) image shown in Fig. 1(b).

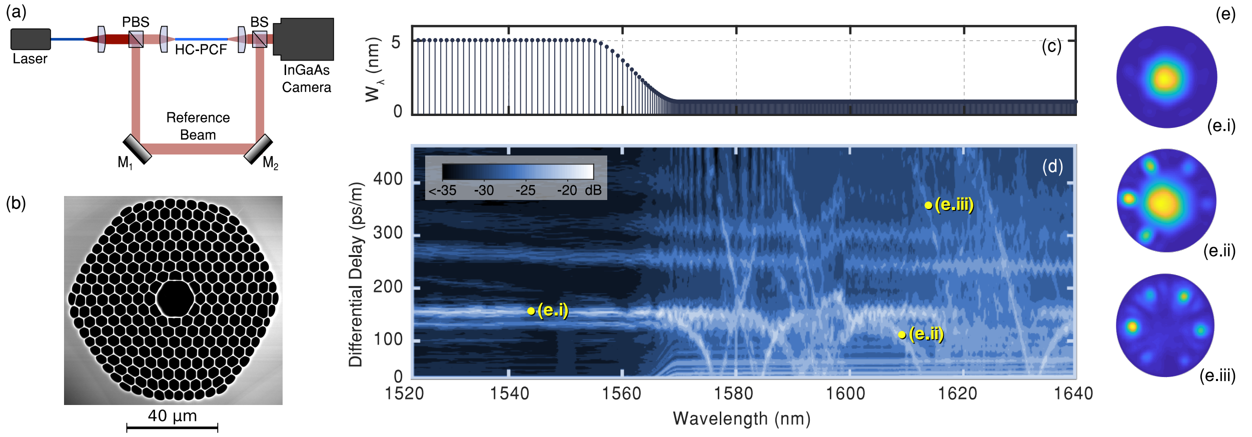

Fig. 1. (a) Experimental setup. (b) SEM image of the characterized 7-cell HC-PCF. (c) Wavelength window size in terms of wavelength. (d) Outcome of wavelength-resolved S^2 method. (e) Mode profiles recovered at the points identified in (d).

The second modification in the S^2 method was the implementation of a variable wavelength window in the spectrogram. To obtain a high differential group delay resolution, a wide wavelength window is necessary. On the other hand, a narrow window is required for high wavelength definition. Thus, this new approach allows us to avoid the trade-off between the resolution in these two domains. Depending on the wavelength window in the spectrogram, we can distinguish between traces with relatively flat differential delay, as the case of core-guided modes, and high-slope curves corresponding to anti-crossing regions where SMs are interacting with the core modes. In order to correctly recover the modes in both low and high slope differential time delay regimes simultaneously, we employed a variable wavelength window spectrogram with an overlap factor of 0.8 between contiguous windows. The wavelength window size (denoted by W_λ) varies from 5 nm to 0.8 pm between 1560 nm and 1570 nm. This transition, which has been smoothed by a raised cosine shape, is shown in Fig. 1(c). The variable wavelength window spectrogram is shown in Fig. 1(d), where core-guided and surface modes can be identified. Fig. 1(e) shows the profiles of the modes recovered at different points on the spectrogram in Fig. 1(d). In this case we presented the recovered mode profile of the fundamental LP_{01}-like mode shown in Fig. 1(e.i), a core-surface coupled mode in Fig. 1(e.ii) and a highly-dispersive mode (pure surface mode) in Fig. 1(e.iii).

In conclusion, we employed a wavelength resolved S^2 method with external reference to recover highly-dispersive modes. Applying this method in a variable window spectrogram, we are able to recover surface modes in a 7-cell HC-PCF.

Acknowledgments: We thank FAPESP (grants 2013/20180-3, 2015/04113-0, 08/57857-2, 2013/20180-3, 08/57857-2) CAPES and CNPq (grant 574017/2008-9). We also thank Corning Incorporated for providing the HC-PCF samples.

References

1. R. Van Uden, R. A. Correa, E. A. Lopez, F. Huijskens, C. Xia, G. Li, A. Schülzgen, H. De Waardt, A. Koonen, and C. Okonkwo, "Ultra-high-density spatial division multiplexing with a few-mode multicore fibre," Nature Photonics **8**, 865 (2014).
2. J. Nicholson, L. Meng, J. Fini, R. Windeler, A. De Santolo, E. Monberg, F. DiMarcello, Y. Dulashko, M. Hassan, and R. Ortiz, "Measuring higher-order modes in a low-loss, hollow-core, photonic-bandgap fiber," Opt. Express **20**, 20,494–20,505 (2012).
3. J. W. Nicholson, A. D. Yablon, S. Ramachandran, and S. Ghalmi, "Spatially and spectrally resolved imaging of modal content in large-mode-area fibers," Opt. Express **16**, 7233–7243 (2008).
4. J. A. West, C. M. Smith, N. F. Borrelli, D. C. Allan, and K. W. Koch, "Surface modes in air-core photonic band-gap fibers," Opt. Express **12**, 1485–1496 (2004).
5. M. Lyu, Z. Lin, G. Li, and G. Situ, "Fast modal decomposition for optical fibers using digital holography," Scientific Reports **7**, 6556 (2017).