Optical and Digital Key Enabling Techniques for SDM-Based Optical Networks

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ABSTRACT

In order to support, in a cost-effective way, the data capacity demand in the context of future 5G networks, a new set of advanced technologies need to be explored, as it is the case of space-division multiplexing (SDM) along with energy efficient coherent detection based modulation formats. This paper presents the recent results on enabled optical networks based on SDM for high capacity optical networks compatible with 5G network infrastructure and data center connectivity. In particular, we demonstrate the viability of using Long-Period Gratings (LPGs) in multi-core fibers (MCFs) to develop different components for multicore-based SDM systems, such as pump couplers and core/wavelength selective multi-core switches and couplers. Moreover, we also present and characterize the performance of different digital signal processing (DSP) algorithms and subsystems supporting optical coherent detection in SDM systems.

Keywords: Coherent detection, digital signal processing, long period grating, generalized Stokes space, space-division multiplexing, space-division demultiplexing.

1. INTRODUCTION

We are now in an era in which traffic growth, dominated by high-definition video streaming, multimedia file sharing, and other information technologies, is increasing faster than system capacity [1]. By 2020 it is estimated that 30 billion devices will connected to a 5G-enabled Internet of Thinks [1]. This combination of broadband services and large scale of network-connected end devices will shortly lead to a capacity crunch, making the increment capacity of optical communication networks mandatory. Such high-demand for capacity is shared by core, metro, and access networks, as well as by optical networks directly supporting 5G infrastructure, i.e., optical fronthaul and backhaul. Spatial-division multiplexing (SDM) has been evolving worldwide as key technology capable of breaking the limitation of conventional single-core single-mode optical fiber based communications systems, where the transmission capacity is considered limited to at most about 0.1 petabits/s [2] due to the limitation on the launched input power or interference between signals [3]. In this context, and due to its natural potencial to increment capacity of optical communications, SDM is being proposed in the context of short-reach application networks, e.g. data-center connectivity or 5G infrastructure transport. Notice that besides its potencial to avoid a future capacity crunch, the SDM concept can also be used for providing a key solutions to such issues as achieving effective infrastructure operation/management and lower power consumption [4]. In [5], a next-generation radio-access network was proposed, employing MCFs in the optical wireless fronthaul and mode-division multiplexing in the backhaul to overcome the capacity limitation of single-mode fibre systems. Recently, multiple-input-multiple-output (MIMO) SDM on MCF was experimentally proposed and evaluated in multiantenna LTE-Advanced systems [6]. MCFs were also proposed as a compact medium to implement fiber-distributed signal processing, which may provide both radio access signal distribution (including MIMO antenna connectivity) and radiofrequency (RF) signal processing [7]. That solution may cover a variety of application scenarios that will be specially demanded in 5G communications [8].

This paper presents the recent results obtained in the context of the project High-Capacity SDM Solutions for Optical Backhaul in 5G Networks and Optical Data Center Connectivity – OPTICAL-5G, focusing the viability demonstration of using Long Period Gratings (LPGs) in MCFs to develop different components for multicore SDM, such as pump couplers and core/wavelength selective multicore (MC) switches and couplers, and the presentation and performance assessment of different digital signal processing (DSP) algorithms for space de-multiplexing in coherent SDM systems.

The remainder of this paper is organized as follows. Section 2 shows a brief overview of the principal optical and digital key enabling techniques in SDM systems. The employment of LPGs in MCFs to develop different components for SDM systems, such as pump couplers and core/wavelength selective multicore switches and couplers is explained in Section 3. In Section 4, we discuss the use of the generalized Stokes space, through Higher-Order Poincaré spheres representation, for the development of advanced digital space-demultiplexing subsystems. The main conclusions are summarized in Section 5.

2. OPTICAL AND DIGITAL KEY ENABLING TECHNIQUES IN SDM SYSTEMS

Analogously to the case of single-mode fiber based systems, the field implementation of fiber-optic SDM systems may strongly benefit form the assistance of both optical and digital key enabling techniques. Such techniques can be employed as key optical subsystems, e.g. optical switchers/couplers or amplifiers, or as compensation/mitigation techniques to deal with the impairments suffered during the signal propagation. As shown in [9], an optical signal propagating in a particular core can be switched to any other core or distributed over all the cores exploring the acousto-optic effect. It was also shown that by tuning the acoustic wave amplitude, one can adjust the amount of optical power transferred between the cores [9]. The light switching/transfer can also be obtained inline through long-period gratings (LPGs) inscribed in heterogeneous multicore fibers (HeMCFs) [10]. The two previous mentioned techniques have the advantage to be inline approaches, thus avoiding coupling/decouplig processes and their respective insertion losses. Regarding optical amplification and also employing an inline approach, a 6-mode and 580-wavelength multiplexed transmission with an dual C+L-band cladding-pumped few-mode EDFA was recently reported in [11]. Such system allowed a total capacity of 266.1 terabit/s over a 90.4 km transmission line at a spectral efficiency of 36.7 bit/s/Hz. In real scenarios, mechanical perturbations are expected to cause mode coupling variations on time scales as short as tens of microseconds, requiring fast adaptive digital multi-input multi-output (MIMO) techniques with tolerable computational complexity [12]. In that way, SDMs must use different signal processing approaches than wireless and SMF systems to ensure near optimum DSP with tolerable complexity.

SDM techniques can also benefit from the combination of coherent detection and advanced digital signal processing (DSP) techniques [13]. A particular example is the adaptive MIMO equalization to compensate for modal crosstalk and modal dispersion. Such techniques can be implemented both in time and frequency domains, with different tradeoffs between performance and computational complexity. The least mean squares (LMS) and recursive least squares (RLS) frequency-domain equalization algorithms have been deeply analyzed in [12]. Recently, a new approach based on Stokes space analysis has also been proposed to signal equalization both in classical single mode fiber systems [14] and in SDM systems. Again, his approach can also be implemented both in time [13] and frequency [15] domains. As shown in [13], the space-demultiplexing algorithm based on higher-order Poincaré spheres (HOPS) has important advantages when compared with its counterparts, e.g. modulation format agnostic, free of training sequences and robust to the local oscillator phase fluctuations and frequency offsets.

3. LPG-BASED OPTICAL PROCESSING IN SDM

LPGs can be employed in MCFs to develop different components for multicore SDM, such as pump couplers and core/wavelength selective MC switches and couplers. The LPGs can be physically inscribed in the fiber or induceÿ for instance, by flexural acoustic waves. A LPG is a type of periodic grating with a large period (100 μm to 1 mm) that promotes the coupling from the propagating core mode to forward-propagating cladding modes at the resonant wavelength. In MCFs, since all the cores share the same cladding mode, the light is coupled, through the cladding mode, from one core to the others that have identical LPGs, see Fig 1-a).

Considering the inscribed LPGs we developed a technique to distribute a single pump source to all the cores using identical LPGs inscribed in the MCF, that promote optical power transfer between all cores. Using a coupled mode method to analyze the power evolution in parallel, identical and uniform LPGs inscribed on MCFs, we demonstrated that, the power launched in one core can be distributed to all the cores, see Fig 1-b). If the MCFs have ring geometry in which all the cores have the same distance to the center of the fiber, the power of one pump is distributed evenly by all the cores, since the coupling coefficient between the fundamental and cladding mode will be equal for all the cores [16]. In other fiber geometries, the differences in these coupling coefficients need to be take into account. In the case of a MCF with one central core and n outer cores at equal distance to the center of the fiber, the power lunched in the central core can be transferred by all the outer cores or distributed evenly by all the cores, by choosing the right cladding mode in order to achieve the desired power transfer [17]. Furthermore,

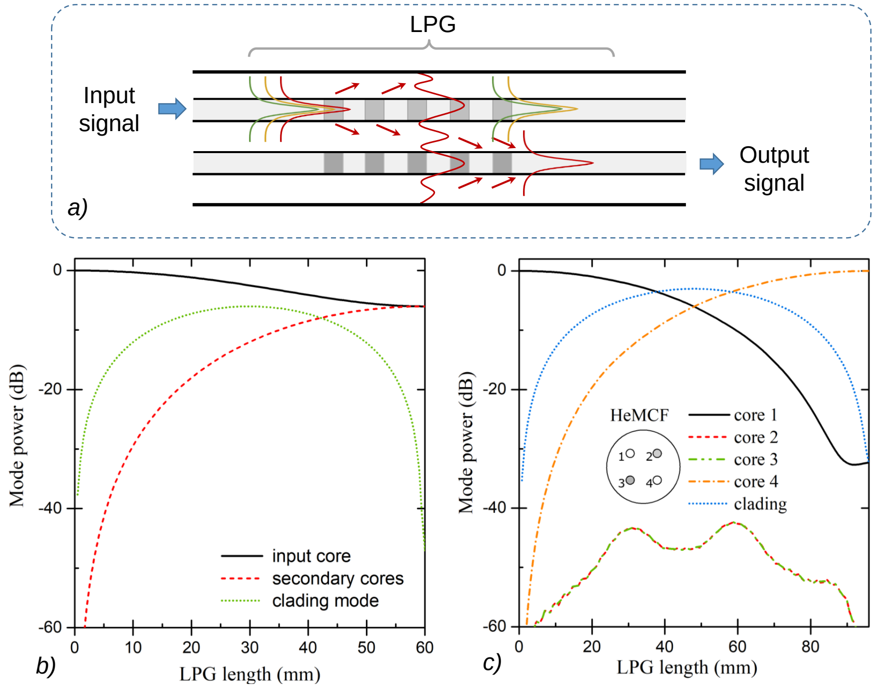

Figure 1: a) - Squematic diagram of a LPG promoting the coupling from the propagating core mode to forward-propagating cladding modes; b) - Power evolution along identical LPGs inscribed in a four core fiber for a wavelength of 1480 nm. The LPG period is 327 mum; c) - Power evolution along identical LPGs inscribed in a HeMCF for the wavelength of 1550 nm, considering the light injected in Core # 1.

if the identical LPGs are inscribed in HeMCF will promote the selective power transfer between identical cores not the other ones, see Fig 1-c), this technique can be used to produce inline selective core switching for MC space division multiplexing [10].

The use of an inscribed long period grating to promote selective coupling between two cores of a 4-core fiber was demonstrated for the first time in [18]. The LPG was inscribed with the arc electric technique, tanking advantage of the fact this technique produces slightly different gratings in each core of the MCF, we were able to achieve power transfer exclusively in two of the four cores. The device was successfully tested for a 200 Gb/s DP-16QAM signal transmission and the results demonstrate that the LPG successfully couples the signal launched in one core to another specific core, not affecting the transmission performance in the remaining cores.

One way to induce LPGs is using flexural acoustic waves, that induce a Bragg structure in the optical fiber with period defined by the acoustic frequency. It was theoretically demonstrated that the power launched in one core of the MCF can be distributed to all the cores by properly adjusting the spatial orientation of the flexural wave. The peak deflection can be used to additionally control the efficiency of power transferred between the cores. Moreover, the acoustic wave frequency can be used to select the central wavelength of the switching band. In heterogeneous MCF, it was demonstrate the in-line wavelength selective core switch between any two cores using two different flexural waves. The conversion efficiency between two cores can also be tuned by adjusting the peak deflection. In addition, an in-line wavelength selective core attenuator using a single flexural wave in HeMCFs, was also proposed [9]. The obtained results demonstrated that this technique can be used to produce tunable core/wavelength selective MC switches and couplers.

4. HIGHER-ORDER POINCARÉ SPHERES BASED DEMULTIPLEXING

In [13], a novel kind of signal representation based on HOPS is introduced, establishing a direct relationship between the Stokes parameters in the *generalized* Stokes space and the Stokes parameters in this novel HOPS representation, see Fig. 2-a). In contrast to the single-mode case, the generalized Stokes space is not suitable to develop DSP tools. However, the signal representation based on HOPS still preserve the symmetry proprieties reported in the single-mode case. Note that, both FMF and MCF approaches can be identically described in HOPS,

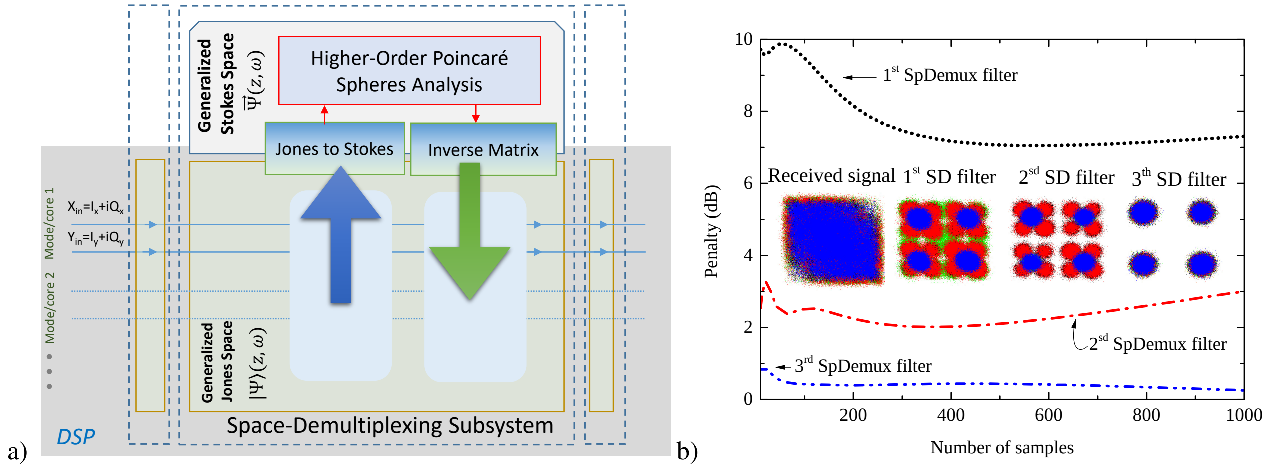

Figure 2: a) - Block diagram of the Higer-Order Poincaré analysis based space demultiplexing, schematically showing the transition between the generalized Jones Space and the generalized Stokes space. b) - Average SNR penalty as a function of the number of processed samples, after applying 1, 2 and 3 SpDemux filters. Insets show the IQ complex constellations for a dual-polarization QPSK signal with a SNR of 17 dB.

since all the tributary signals are coupled. In the generalized Jones space, a multimodal signal can be written as a complex ket vector,

$$|\Psi\rangle = (\upsilon_1, \upsilon_2, ...\upsilon_h, ...\upsilon_{2n})^T \ , \tag{1}$$

where υ_i is the electric filed of the i tributary signal, with $i = 1...2n$ where n denotes the number of modes/cores supported by the SDM system, multiplexed in the spatial mode and in the polarization state. This signal can be represented in $g_s = \binom{2n}{2}$ HOPS, with the components of the Stokes vector $\overrightarrow{\Psi}^{(f,g)}$ written as,

$$\Psi_j^{(f,g)} = \langle\Psi|\,\mathbf{\Lambda}_j^{(f,g)}\,|\Psi\rangle \ , \tag{2}$$

with $j = 1, 2, 3,\ f = 1, 2..., 2n-1$ and $g = f+1,\ ...,\ 2n$. In Eq. (2), the superscript indices, g and f, indicate the υ_f and υ_g signals selected from (1), and further details about the $\mathbf{\Lambda}_j^{(f,g)}$ operators can be found in [13].

The crosstalk among all the pairs of tributaries is sequentially equalized in order to fully demultiplexed the received signal. Thereby, it is assumed that the crosstalk operator induced by the propagation through the fiber can be decomposed in g_s canonical operators [13]. Each operator takes into account the crosstalk between a given pair of tributary signals. We proposed a different approach to perform the space-demultiplexing based on the HOPS representation, where the inverse channel matrix is calculated in an iterative way [19]. Such new approach allows to substantially decrease the computational effort of the previous HOPS-based space-demultiplexing algorithm. In Fig. 2-b) we show the average SNR penalty as a function of the number of processed samples, after applying 1, 2 and 3 space demultiplexing (SpDemux) filters of the simplified algorithm. Insets show the IQ complex constellations for a dual-polarization QPSK signal with a SNR of 17 dB. Results show applying 3 SpDemux filters is enough to achieve negligible SNR penalty values. Along with the fast convergence speed demonstrated in Fig. 2-b), this algorithm presents other important advantages when compared with other counterparts, e.g. data-aided NLMS algorithms, like be modulation format agnostic, free of training sequences and robust to the local oscillator phase fluctuations and frequency offsets.

5. CONCLUSIONS

We have presented the recent results obtained in the context of the project High-Capacity SDM Solutions for Optical Backhaul in 5G Networks and Optical Data Center Connectivity - OPTICAL-5G. In particular, we have demonstrated the viability of using LPGs in MCFs to develop different components for multicore SDM, such as pump couplers and core/wavelength selective MC switches and couplers. Moreover, we also have addressed the issue of digital equalization in SDM systems, presenting and discussing the performance HOPS-based space demultiplexing algorithms.

ACKNOWLEDGEMENTS

This work was supported in part by Fundação para a Ciência e a Tecnologia (FCT) through national funds, by the European Regional Development Fund (FEDER), through the Competitiveness and Internationalization Operational Programme (COMPETE 2020) of the Portugal 2020 framework, under the projects POCI-01-0145-FEDER-029405 and project UID/EEA/50008/2013 (actions COHERENTINUOUS, SDMThechs, and OPTICAL-5G), and through the doctoral grant SFRH/BD/102631/2014.

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