29 MAY 2018
Research article
INFORMATION TECHNOLOGY

Generating and Characterizing Cylindrical Vector Beams

> The following text is from one of the finalists in the 2017 SARA Abstract Contest. The writer was awarded First Place for the clarity and quality of the research project abstract. The other texts submitted to the SARA Contest are also available.

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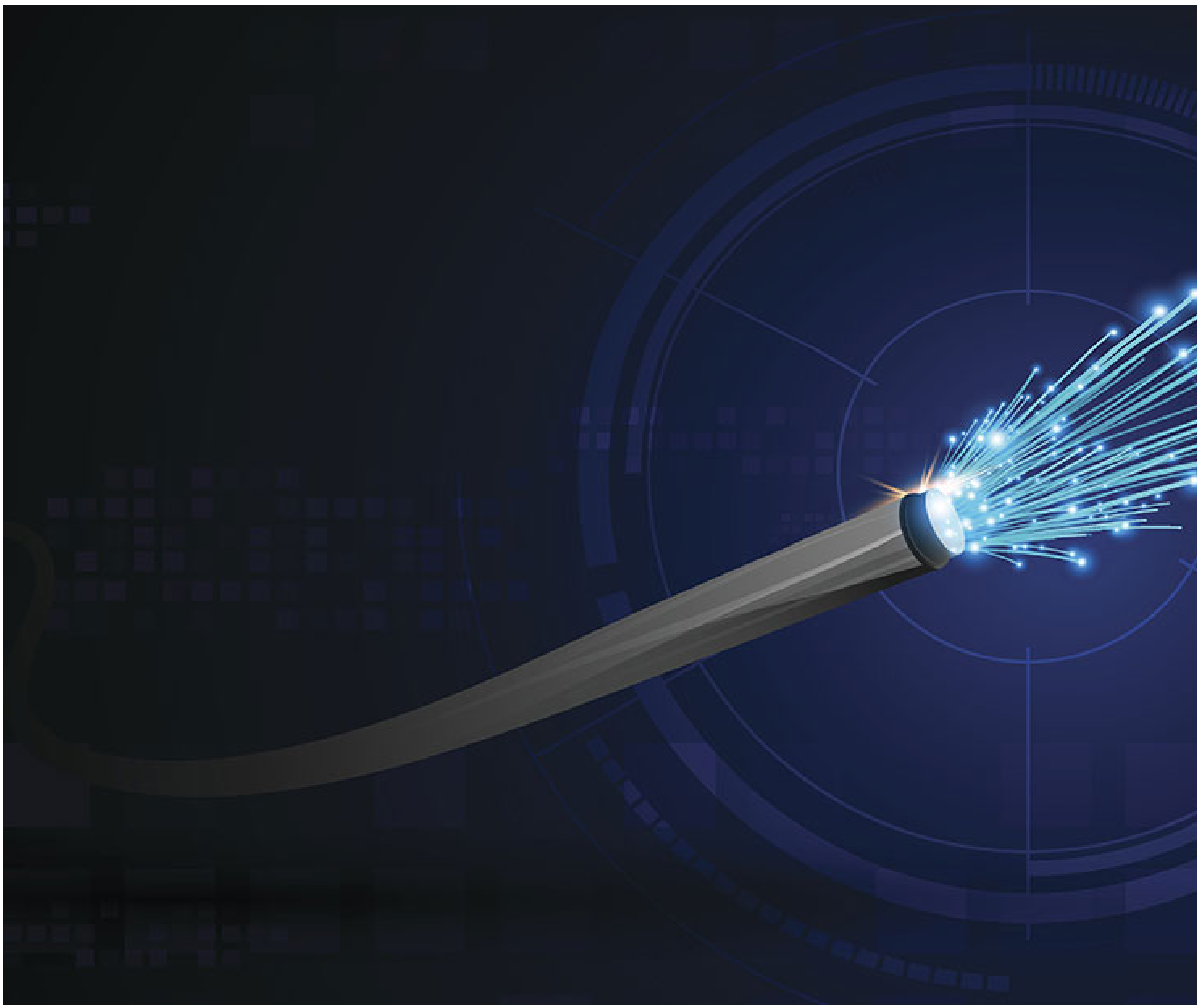

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SUMMARY

Fuelled by the ever-increasing demand for high-bandwidth multimedia applications, the ultimate data transmission capacity of a standard single-mode fiber (SMF)—the backbone of the Internet—is predicted to be reached within the next decade. Space division multiplexing (SDM) aims to harness the rich spatial mode diversities available in multimode fibers (MMF) and few-mode fibers (FMF) towards increasing the transmission capacity within a single strand of fiber [1]. Moreover, it has been suggested that the same SDM techniques developed for generating and controlling modal transmission in MMF and FMF, could be utilized towards multi-parameter fiber-optic sensing [2].

Research Objectives

The first objective of this project is to investigate specially designed FMFs as well as develop novel methods for the excitation and control of the elusive higher-order vector modes that can propagate in such specialty FMFs. Contrary to the classical scalar modes of FMF, the vector modes possess special polarization properties as well as the unique ability to carry quantum states of orbital angular momentum (OAM) [3] that provide new degrees of freedom for both optical communications and sensing. The second objective is to apply the developed techniques for the characterization of next-generation SDM communication links towards the multi-parameter distributed fiber-optic sensing (of temperature and strain) in civil engineering structures and for niche biomedical sensors such as spinal cord trauma monitoring.

Methodology

The first task is to design an efficient mode converter to selectively excite the desired vector mode(s). This will be achieved via a tunable mechanical long-period fiber grating (LPFG) [4]. An alternate method of generating the vector modes using a spatial light modulator (SLM) will be investigated and compared with the LPFG. ii) The second task will be to transmit and independently detect at the FMF output the co-propagating modes by means of a de-multiplexing device in the form of a SLM. iii) Next, the accurate characterization of these vector modes will be accomplished via the generation of a dynamic Brillouin grating (DBG) in the fiber, an advanced metrological technique with promising applications in fiber-optic communications [5] and distributed fiber sensing [6]. iv) The final phase will be to harness the vector modes in the development of novel SDM characterization techniques and in multi-parameter distributed fiber-optic sensors.

Results

So far, we have demonstrated the selective excitation of cylindrical vector modes in FMF using a long period fiber grating [4] and studied their non-linear Brillouin properties towards the fully distributed characterization of telecom links with potential applications in distributed fiber sensing [4, 7]. In this paper, we reported the measurement of the Brillouin gain spectra (as shown in Figure 1) of vector modes in a few-mode fiber for the first time using a simple heterodyne detection technique. A tunable LPFG is used to selectively excite the vector modes supported by the few-mode fiber. Further, we demonstrate the non-destructive measurement of the absolute effective refractive indices

(n_{eff}) of vector modes with ~10−4 accuracy based on the acquired Brillouin frequency shifts of the modes. The proposed technique represents a new tool for probing and controlling vector modes as well as modes carrying orbital angular momentum in optical fibers with potential applications in advanced optical communications and multi-parameter fiber-optic sensing.

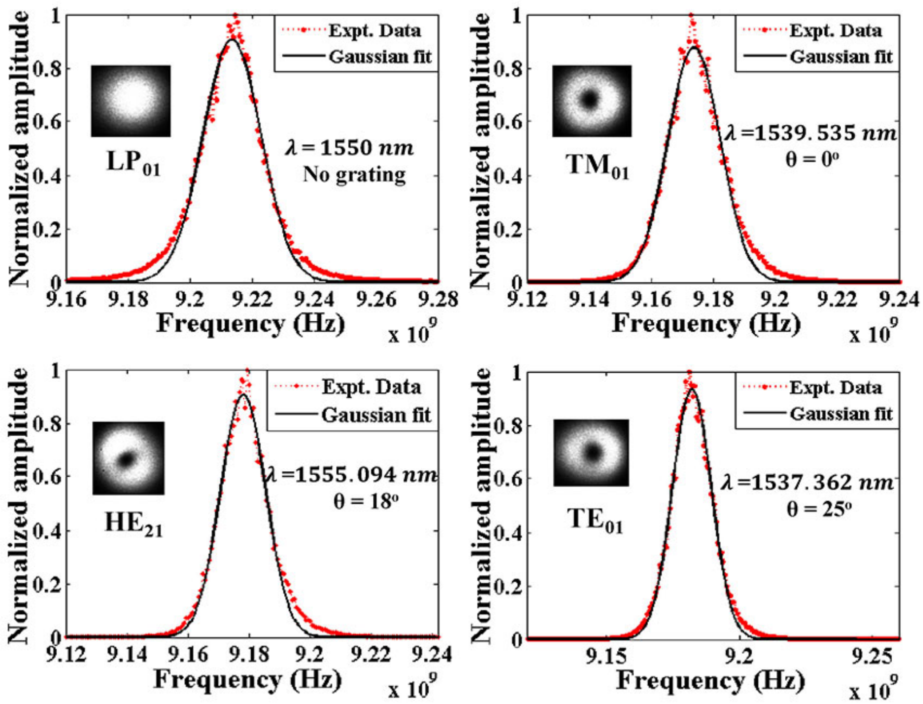

Fig. 1. Measured Brillouin gain spectra for fundamental and high-order vector modes, and corresponding Gaussian fit curves [7].

Recently, we have been working on the generation of perfect cylindrical vector beams (PCVB) using the Fourier transformation of Bessel-Gauss vector beams [8]. Precise control over the ring diameter and ring width of vortex beams (i.e. beams carrying OAM) was recently achieved through the generation of perfect vortex beams, as demonstrated by a number of research groups [9, 10]. These recent works report the ability to maintain the dimensions of the beam intensity pattern irrespective of their topological charge. Furthermore, the reported new class of perfect vector vortex beams has been demonstrated with tailorable ring diameter irrespective of the polarization order. Though to the best of our knowledge, the independent control of the ring diameter and ring width for PCVB has not yet been demonstrated in its entirety. So far, efforts towards the generation of PCVBs that would enable one to fully tailor the intensity profile of the CVBs of interest have yielded PCVBs with tunable ring diameter only that were of limited purity [11] (showing residual light intensity in the beams' centre) via a method of limited flexibility due to the use of static (Pancharatnam-Berry phase) optical element [11]. In this work, we demonstrate the generation of arbitrary PCVBs whose transverse intensity profile (i.e. ring width and ring diameter) can be independently and easily controlled via an iris and a diffractive phase mask implemented on a programmable SLM as shown in Figure 2.

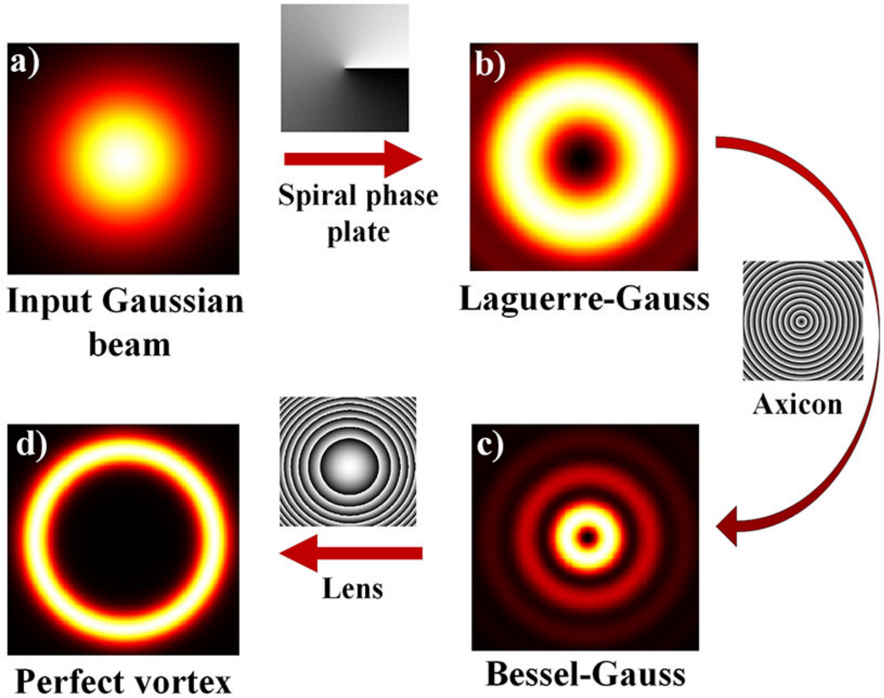

Fig 2. Experimental and simulated generation of PCVBs. The type of PCVB generated (TM01, TE01, even and odd HE21) depends on the specific topological charges and phase differences ascribed to each interfering beam [8].

The demonstration of PCVBs is implemented via an interferometric method employing a spatial light modulator that allows the independent control of the ring diameter and ring width of the PCVB. The proposed scheme enables to generate different types of CVB with precise user-defined transverse dimensions. The dynamic control of the ring width, ring diameter, and the specific type of PCVBs desired (in this work: TM_{01}, TE_{01}, odd and even HE_{21} modes) is theoretically as well as experimentally demonstrated. The ability to generate perfect cylindrical vector beams has implications for the efficient launch of exotic optical modes in specialty fibers, in the field of optical trapping as well as for super-resolution microscopy.

IMPACT

The proposed research will contribute to revealing the underlying physics that guide the rich light-matter interactions inside few-mode fibers and develop new scientific methods to generate, transmit, shape and characterize the vector modes that constitute the fundamental basis set of light propagation in these important waveguides. In doing so, the research outcomes will have a direct impact on the development of novel metrological techniques for next-generation communication networks, a strategic area of contemporary socioeconomic development, as well as in the field of distributed fiber-optic sensing that promises new practical advances for the live remote monitoring of civil engineering structures and in biomedical research.

Additional information

For more information on this research, please read the following articles:

Pradhan, P., et al., The Brillouin gain of vector modes in a few-mode fiber. Scientific Reports, 2017. 7.

Pradhan, P., Sharma, M., & Ung, B. (2018). Generation of perfect cylindrical vector beams with complete control over the ring width and ring diameter. IEEE Photonics Journal, 10(1).

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Field(s) of expertise :	Photonic devices Optical communications Doped optical fibers

References

1. Richardson, D., J. Fini, and L. Nelson, Space-division multiplexing in optical fibres. Nature Photonics, 2013. 7(5): p. 354-362.

2. Li, A., et al., Few-mode fiber based optical sensors. Optics express, 2015. 23(2): p. 1139-1150.

3. Ung, B., et al., Few-mode fiber with inverse-parabolic graded-index profile for transmission of OAM-carrying modes. Optics express, 2014. 22(15): p. 18044-18055.

4. Pradhan, P., et al. Excitation of vector modes in few-mode fiber using wire-based mechanical long period fiber grating. in Photonics North, 2015. 2015. IEEE.

5. Santagiustina, M., et al., All-optical signal processing using dynamic Brillouin gratings. Scientific reports, 2013. 3.

6. Mizuno, Y., et al., Brillouin scattering in multi-core optical fibers for sensing applications. Scientific reports, 2015. 5.

7. Pradhan, P., et al., The Brillouin gain of vector modes in a few-mode fiber. Scientific Reports, 2017. 7.

8. Pradhan, P., Sharma, M., & Ung, B. (2018). Generation of perfect cylindrical vector beams with complete control over the ring width and ring diameter. IEEE Photonics Journal, 10(1).

9. Li, P., et al., Generation of perfect vectorial vortex beams. Optics Letters, 2016. 41(10): p. 2205-2208.

10. Ostrovsky, A.S., C. Rickenstorff-Parrao, and V. Arrizón, Generation of the “perfect” optical vortex using a liquid-crystal spatial light modulator. Optics letters, 2013. 38(4): p. 534-536.

11. Liu, Y., et al., Generation of perfect vortex and vector beams based on Pancharatnam-Berry phase elements. Scientific Reports, 2017. 7.

Images references