Modal Characterization of Hollow-core Photonic Bandgap Fibers in the Time-domain

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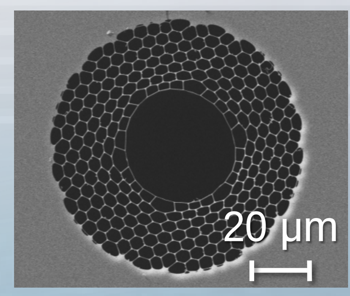
ABSTRACT

We present a collection of modal characterization techniques based on time-of-flight, that are applicable to multimode fibers for data transmission, with particular focus on hollow-core photonic bandgap fibers.

1. INTRODUCTION

The explosion of bandwidth-hungry internet applications and services, as well as the rapid narrowing of the digital divide, has resulted in a steady exponential growth in internet traffic, necessitating drastic improvements in the existing backbone fiber network to commensurately increase its transmission capacity. The information carrying capacity of conventional solid-core, single-mode fiber is reaching its fundamental maximum, the nonlinear Shannon limit [1], spurring the urgent need for radically new fiber designs and network architectures. In response, **hollow-core photonic bandgap fibers** (HC-PBGFs) have received considerable recent interest because of their attractive merits [2], and their applicability with **mode-division multiplexing** (MDM) to increase capacity. Recent first demonstrations of a 37-cell (37c) HC-PBGF have verified this ability [3,4], albeit using complex digital signal processing (DSP) to undo the effects of sizeable mode coupling in the fiber. Efficient use of higher-order modes (HOMs) requires careful **study of the nature and extent of mode coupling in these fibers**. In this work, we describe the modal characterization of HC-PBGFs using the simple time-of-flight method, with particular emphasis on the versatility of the technique in a number of measurements.



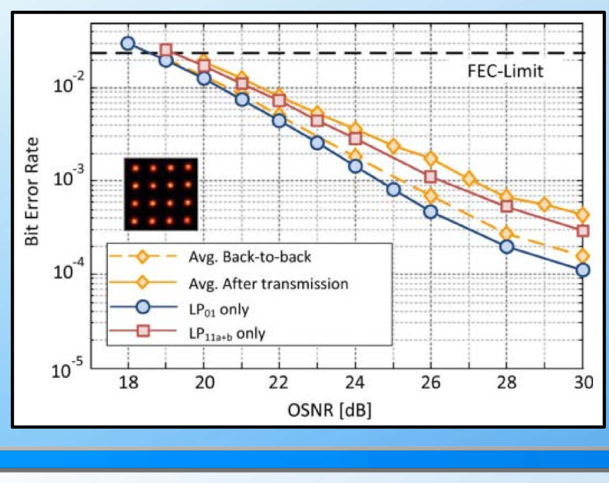
37-cell HC-PBGF (*Jung et al*. [3])

- Low loss
- Low latency
- Ultralow nonlinearity
- High multimode capacity

2. RECENT TELE/DATACOMS ACTIVITIES USING HC-PBGFS

1. 37c single-mode transmission at λ = 1.55 µm [4]
2. 73.7 Tb/s MDM using 3 modes at λ = 1.55 µm [5]
3. Single-mode transmission at λ = 2 µm [6]
4. Low-latency data center link [7]
5. 78.4 km recirculating loop [8]

… but behaviour of HOMs is still not completely understood.



3. TIME-OF-FLIGHT

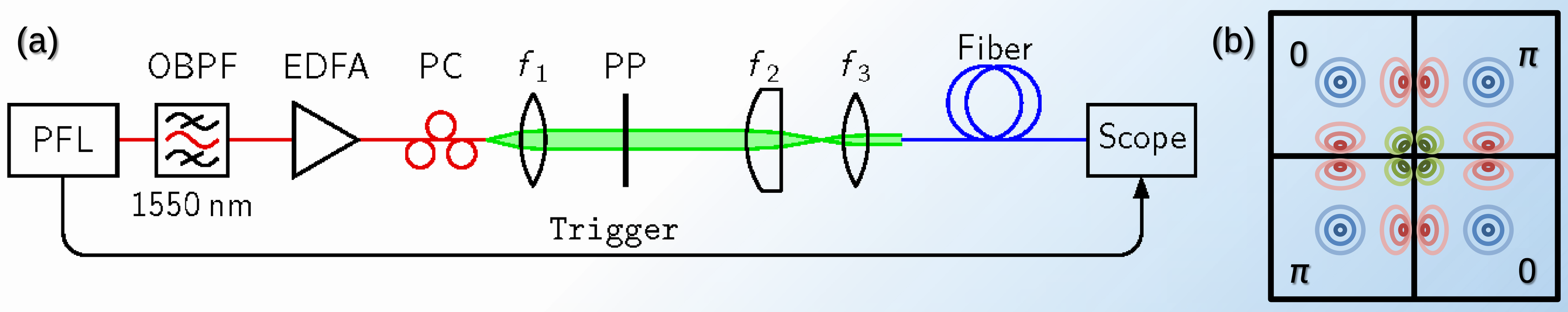


Figure 1. (a) ToF experimental setup. PFL: pulsed fiber laser; OBPF: optical bandpass filter; EDFA: erbium-doped fiber amplifier; PC: polarization controller; PP: phase plate. (b) PP transverse face showing relative phase regions and excited LP mode profiles.

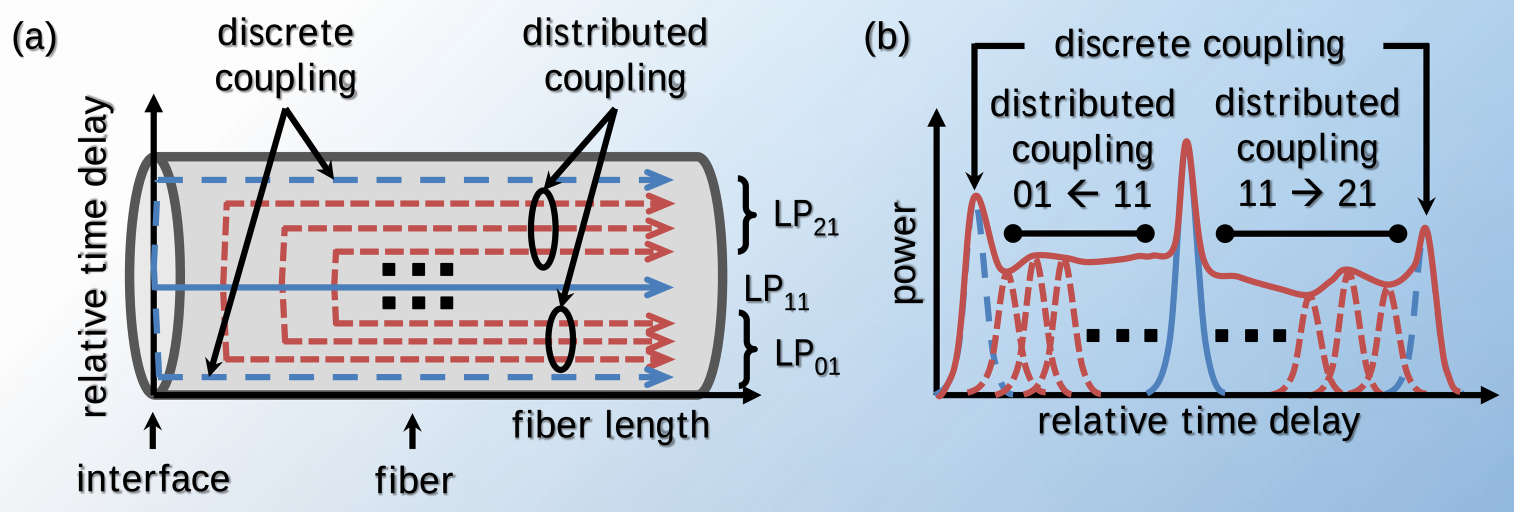
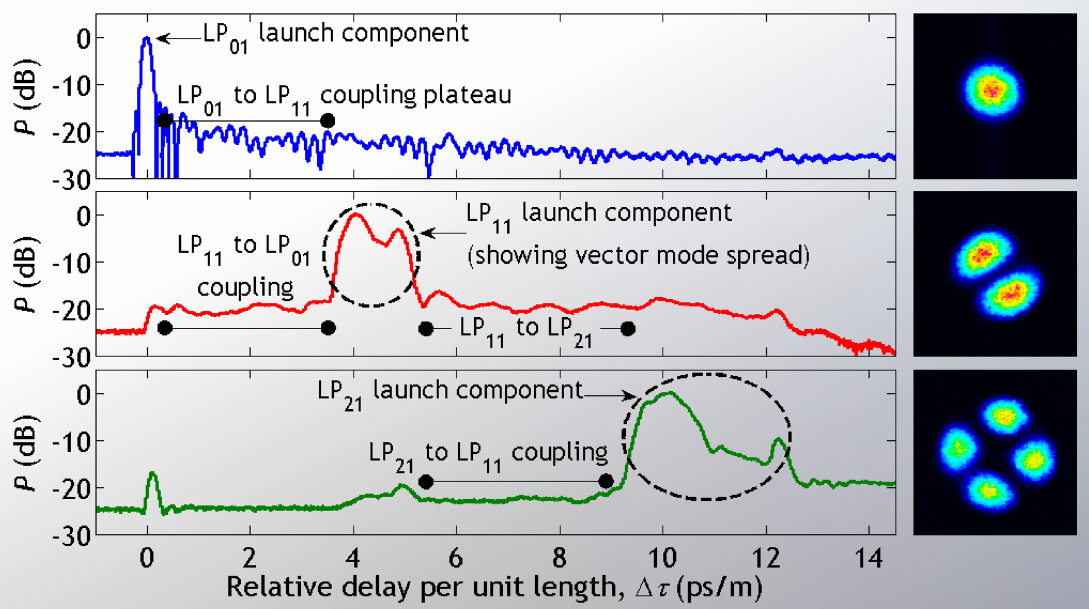


Figure 2. (a) Discrete versus distributed mode coupling; LP_{11} is launched and couples to both LP_{01} and LP_{21}. (b) ToF trace. Distributed coupling contributions form plateaus. (Adapted from [9].)

The time-of-flight (ToF) technique is a time-domain method that can provide useful information about the modal content in a fiber. Modal dispersion is exploited to temporally separate modes during propagation. Several features of ToF include:

1. Ability to distinguish between discrete and distributed mode coupling
2. Information about differential group delays between modes
3. Real-time response allowing interactive launch optimization, and identification of mode peaks
4. Inherent requirement of long fiber length to disperse and subsequently resolve individual mode peaks:
   a) Measurement reflects true modal behaviour, as opposed to simulated/extrapolated
   b) High-loss HOMs diminish after short lengths, so the output trace shows only the actual guided modes
5. Simple set-up with few components

4. MODE COUPLING ANALYSIS



1. Experimental results provide measures of discrete and distributed coupling.
2. Information from extinction ratios:
   a) Between discrete peaks — quality of launch
   b) Between launch peak and distributed plateaus — magnitude of coupling
3. Vector component spread is clearly visible.

Figure 3. ToF measurements for mode-selective launches in a 37c HC-PBGF, showing discrete peaks and distributed coupling plateaus. *P* = normalized power. Respective captured mode profiles inset.

5. LONGITUDINAL DEFECT ANALYSIS

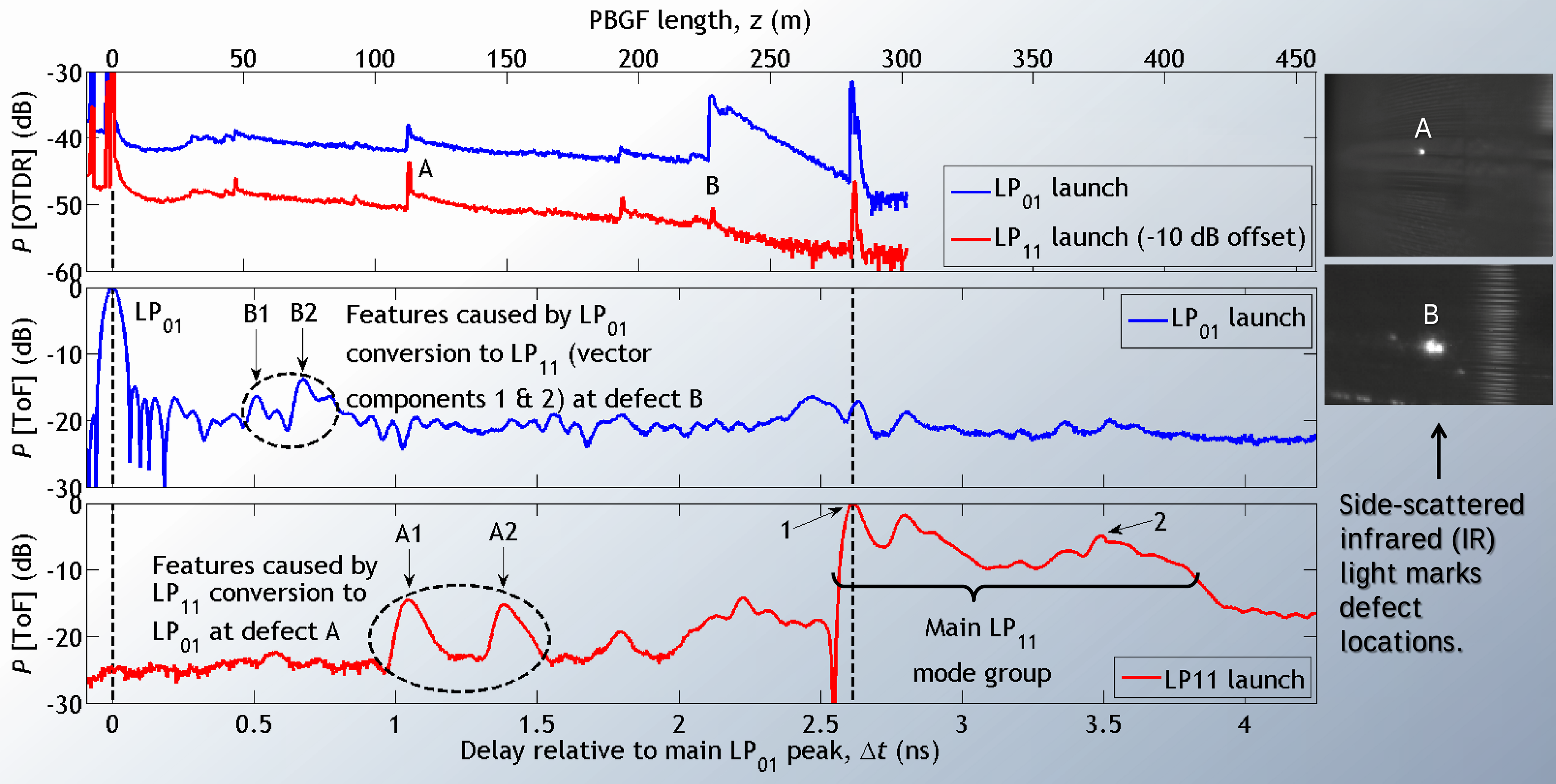


Figure 4. Mode-selective OTDR and ToF traces (aligned for comparison) of LP_{01} and LP_{11} launches on a 19c HC-PBGF with longitudinal defects. Inset: side-scattered IR at defects. From [10].

1. Defects can cause mode conversion. This is exploited to show a 1-to-1 correspondence between the OTDR spatial positions and ToF temporal locations of the defect features.
2. We verify this by gently tapping the fiber at IR side-scattering points to induce perturbations seen in real-time at the respective ToF defect locations.
3. Certain defects may cause preferential asymmetrical coupling, e.g. from LP_{11} to LP_{01} but not vice-versa. This might depend on the physical structure of the defect.
4. ToF enhances OTDR data by shedding light on modal behavior at defects.

6. MODAL AND CHROMATIC DISPERSION ANALYSIS

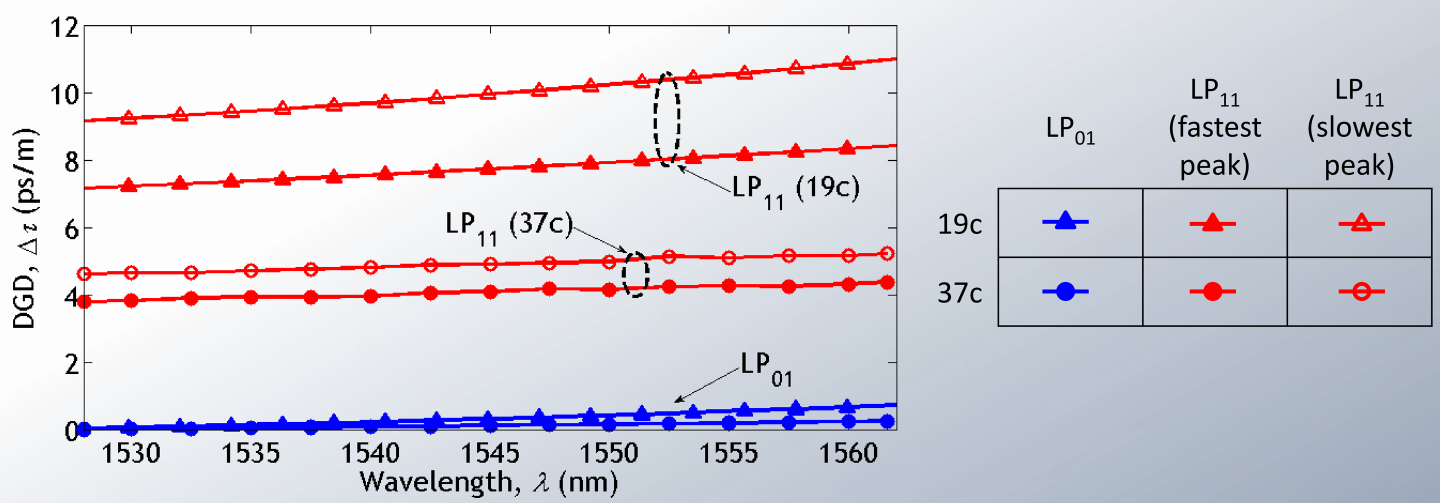


Figure 5. DGD results comparing 19c and 37c HC-PBGFs. Circled lines indicate fastest and slowest LP_{11} vector mode peaks of respective fibers.

1. Differential group delay (DGD) across the C-band is obtained by measuring the temporal separation of LP_{01} and LP_{11} peaks. Dispersion can be measured from the slope of DGD curves.
2. Relative delays of fastest and slowest vector mode peaks indicate LP_{11} mode group spread.
3. 19c PBGFs appear to have longer DGD, more dispersion, and greater mode spreading, possibly due to larger mode overlap with the air core/glass strut interface.

7. CONCLUSIONS

1. ToF is a useful real-time method for analyzing modal content in fibers.
2. HC-PBGFs show significant mode coupling, both discrete and distributed. Thus, receiver-end DSP is likely unavoidable if MDM is to be implemented.
3. ToF also enables other studies, such as dispersion and defect analysis.

8. FUTURE PROSPECTS

1. Extend selective excitation to other HOMs, e.g. LP_{02}, LP_{31}, LP_{41}
2. Develop complementary numerical model to fit with experimental traces and quantify coupling strengths.
3. Assess if ToF can provide information on mode-dependent loss.
4. Relate the physical structure of defects to induced modal behavior.
5. Find trends in coupling/loss behaviour over different core sizes.

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