

# High-Order Mode Brillouin Fiber Lasers Based on Intra- and Inter-Modal SBS

Ning Wang<sup>1,\*</sup>, J. C. Alvarado-Zacarias<sup>1</sup>, Md Selim Habib<sup>1</sup>, He Wen<sup>1</sup>, Yuanhang Zhang<sup>1</sup>, J. E. Antonio-Lopez<sup>1</sup>, Pierre Sillard<sup>2</sup>, A. Amezcua-Correa<sup>2</sup>, R. Amezcua-Correa<sup>1</sup> and Guifang Li<sup>1</sup>

<sup>1</sup>CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, Florida, 32816, USA

<sup>2</sup>Prysmian Group, Parc des Industried Artois Flandres, Douvrin, 62138, France

\*ningwang@knights.ucf.edu

**Abstract:** We experimentally demonstrated LP<sub>11</sub> mode Brillouin fiber lasers based on both intra- and inter-modal SBS. The OSNRs were over 65 dB, and their mode profiles were clearly observed for both cases. © 2019 The Author(s)  
**OCIS codes:** 060.2310, 140.3510, 290.5900.

## 1. Introduction

Stimulated Brillouin scattering (SBS) is a prominent nonlinear effect in optical fibers. It can be described as a nonlinear interaction among the pumps, the Stokes waves and the acoustic wave. Brillouin fiber laser (BFL) could be realized by using SBS to provide gain for the signal travelling in the backward direction. The optical signal-to-noise ratio (OSNR) of a BFL is much higher than the pump laser due to the stronger damping of the acoustic field compared to the optical field [1]. Additionally, the linewidth of the Stokes wave is very narrow, a BFL with a linewidth of tens of Hz has been demonstrated [2].

Lasers of high-order mode (HOM) have been intensely investigated in the recent years because of their advantages in a number of applications, ranging from fiber sensing to laser material processing. Several techniques have been proposed to construct HOM lasers. By using a rare-earth doped few-mode fiber (FMF) with intra-cavity mode-selective elements, it's possible to generate a specific LP mode in the laser [3,4]. Intermodal four-wave mixing can also be used to realize HOM lasers in a multimode fiber (MMF) [5]. Recently, a BFL of LP<sub>01</sub> and LP<sub>11</sub> modes in a FMF has been reported [6]. However, in that experiment, the mode-selective coupler was placed outside the ring cavity, and the mode purity was compromised due to the intermodal SBS effect.

In this paper, we propose HOM BFLs based on both intra- and inter-modal SBS in FMFs. A pair of mode-selective photonic lanterns (MSPLs) were placed inside the ring cavity to act as spatial filters to improve the mode quality. We experimentally demonstrated lasing in the LP<sub>11</sub> modes for both cases. The slope efficiencies, optical spectra, OSNRs, and mode intensity profiles of the BFLs were characterized.

## 2. Experimental setup and results

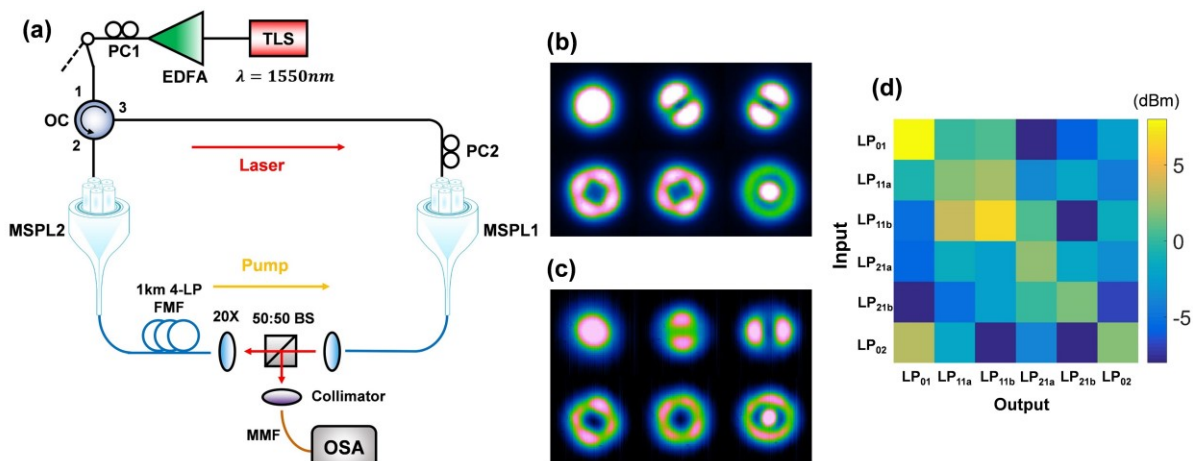


Fig. 1. (a) Experimental setup for the generation of HOM BFLs; output mode profiles of (b) MSPL1 and (c) MSPL2 measured at 1550 nm; (d) mode transfer matrix of a pair of MSPLs.

The experimental setup for the HOM BFLs is shown in Fig. 1(a). The pump was a tunable laser source (TLS) with a wavelength of 1550 nm, amplified by an EDFA. For intra-modal Brillouin lasing, the pump traveled through the circulator and was launched into MSPL2 to evolve into the desired LP mode. The output of MSPL2 was spliced to

1km of 4-LP mode FMF. The back scattered Stokes wave of the same mode went through the circulator from port 2 to port 3, and was injected into MSPL1 with the port mapping to the same LP mode. The HOM signal from MSPL1 was coupled back into the 1km FMF and circulated clockwise as shown by the red arrow. For the intermodal Brillouin lasing, the pump was launched into the LP<sub>01</sub> port of MSPL2. The ports correspond to the desired HOM for both MSPLs were connected to port 2 and 3 of the circulator. Due to the intermodal SBS effect, the selected HOM can lase even with the fundamental mode as the pump. The laser came out from a 3dB beam splitter (BS). We used a fiber collimator to couple the laser into a piece of MMF, and observed its optical spectra by an optical spectrum analyzer (OSA). Fig. 1(b) and (c) show the output mode profiles of MSPL1 and MSPL2, respectively. The six lowest-order LP modes were clearly observed. We measured the mode transfer matrix from MSPL1 to MSPL2 at 1550 nm, the result is shown in Fig. 1(d). The mode selectivity between different mode groups is around 5 dB.

We measured the laser power in the LP<sub>01</sub> mode and LP<sub>11</sub> mode based on both intra- and inter-modal SBS, as shown in Fig. 2(a). For LP<sub>01</sub> SBS lasing mode, the threshold pump power is 40 mW, and the slope efficiency is 11.6%. The low slope efficiency is partly because the polarization states between the pump and Stokes wave were not perfectly aligned. Another reason is that the insertion losses of our MSPLs are larger than the typical values. The slope efficiencies for LP<sub>11</sub> SBS lasing mode based on intra- and inter-modal SBS are 8.1% and 7.4%, respectively. The lower laser power is mainly caused by a larger insertion loss of the lantern pair compared to the LP<sub>01</sub> mode, and smaller overlap integral between the optical and guided acoustic fields. The optical spectra and mode profile of the LP<sub>01</sub> mode BFL are shown in Fig. 2(b). The frequency downshift between the pump and the laser is around 0.1 nm. The small peak on the laser spectra came from the reflection of the pump at the end of the FMF, which can be suppressed by angel cleaving the fiber end. The OSNR was 68.6 dB, nearly 20 dB higher than that of the pump. Fig. 2(c) and (d) indicate the results for LP<sub>11</sub> lasing s based on intra- and inter-modal SBS. The shapes of their optical spectra looks similar, and the OSNRs were measured to be 68.2 dB and 66.8 dB. All the output mode profiles of the SBS lasers were clearly observed by a CCD camera.

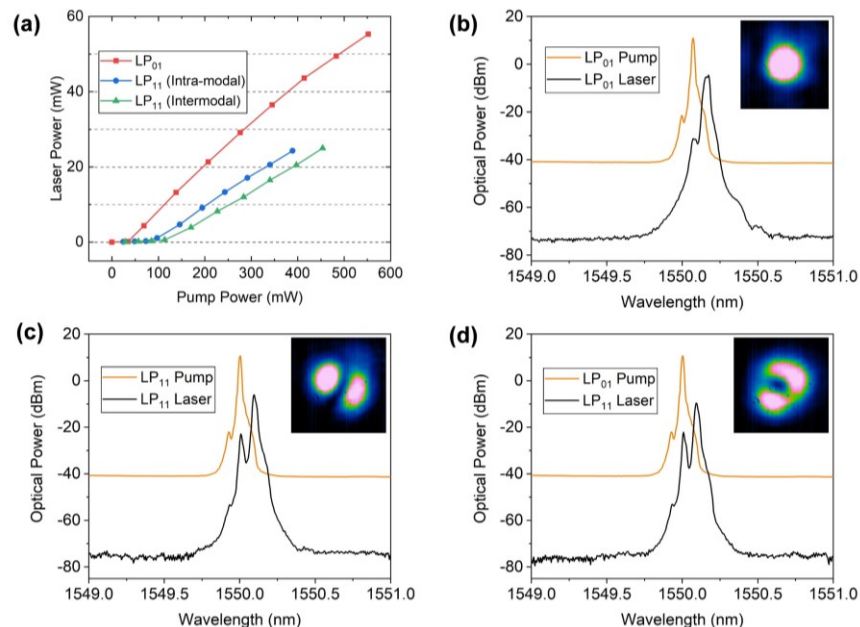


Fig. 2. (a) Laser power vs. pump power for the LP<sub>01</sub> and LP<sub>11</sub> lasing modes; (b) optical spectra for the LP<sub>01</sub> mode BFL with its pump; inset: laser's mode profile; optical spectra and mode profiles for the LP<sub>11</sub> mode BFL based on (c) intra- and (d) inter-modal SBS.

### 3. Conclusion

We have experimentally demonstrated the LP<sub>11</sub> mode BFLs based on both intra- and inter-modal SBS in a 1 km FMF. The SBS lasing with over 25 mW output power and nearly 70 dB OSNR were observed for both cases.

### 4. References

- [1] J. Wang, et al., *Opt. Express*, **23**(22), 28978-28984 (2015).
- [2] Z. Ou, et al., *Photon. Technol. Lett.*, **26**(20), 2058-2061 (2014).
- [3] J. M. O. Daniel et al., *Opt. Exp.*, **21**(24), 29442-29448 (2013).
- [4] N. Wang, et al., *Opt. Express*, **26**(25), 32777-32787 (2018).
- [5] J. Demas, et al., *CLEO 2017*, paper JTh5A.8 (2017).
- [6] X. Heng, et al., *Opt. Lett.*, **43**(17), 4172-4175 (2018).