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We experimentally demonstrate a stabilized singlefrequency Brillouin fiber laser operating at 1.06 µm by means of a passive highly nonlinear fiber (HNLF) ring cavity combined with a phase-locking loop scheme. The stimulated Brillouin scattering efficiency is first investigated in distinct single-mode germanosilicate core fibers with increasing GeO₂ content. The most suitable fiber, namely 21 mol.% GeO₂ core fiber, is used as Brillouin gain medium in the laser cavity made with a 15-m-longsegment. A Stokes lasing threshold of 140 mW is reported. We also show significant linewidth narrowing (below 1-kHz) as well as frequency noise reduction compared to that of the initial pump in our mode-hop free Brillouin fiber laser.

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1. INTRODUCTION

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Stimulated Brillouin Scattering (SBS) in optical waveguides is 5 a nonlinear effect that occurs when the optical field interacts 6 with acoustic waves through electrostriction and photo-elastic 7 phenomena [1, 2]. Several studies based on the SBS process 8 have been extensively demonstrated for many important appli-9 cations [3–7]. Among these, we distinguish the Brillouin lasers 10 which have attracted significant interest as ultra-high coherence 11 light sources with sub-Hertz linewidth in simple all-fiber pas-12 sive optical cavities [8] and in high-Q microresonators [9, 10] 13 suitable for applications in optical communications and LIDAR 14 systems. To date, most of Brillouin lasers have been designed 15 to operate in the telecom bands. However, there is a need to de-16 velop narrow-linewidth, low-noise and high-power laser sources 17 at shorter wavelengths for applications covering this spectral 18 region such as sensing, high-resolution metrology and develop-19 20 ment of space-embarked systems, for inter-satellite and satellite 21 to ground communications [11–13].

So far, only a few studies on Brillouin fiber lasers (BFLs) have been reported around 1 µm. For instance, Wang *et al.* reported a high-power all-fiber cavity laser with high slope efficiency at 1 µm wavelength [14]. In particular, they showed a single-frequency BFL of 3 kHz operating at a maximum output power of 1.4 W. Very recently, Tao et al. demonstrated a high-power single-polarization, single-frequency 1064 nm BFL based on a larger mode area polarization-maintaining fiber [15]. A maximum output BFL power of 4.9 W was achieved, while the linewidth was 170 kHz. In the same way, a high-power all-polarization-maintaining hybrid Brillouin/ytterbium fiber laser operating at 1064 nm was demonstrated by adopting largemode-area fiber with core/cladding diameter of 20/400 µm [16]. Single-frequency BFL with a record output power of 23 W was achieved. However, these Brillouin laser did not present a very marked linewidth narrowing compared to the pump, and stabilization schemes for mode-hopping suppression were not implemented.

In this paper, we demonstrate a stabilized single-frequency Brillouin laser operating around 1-µm based on a highlynonlinear germanosilicate fiber as the Brillouin gain medium. First, we characterize SBS at 1-µm pump wavelength in three distinct doped-core optical fibers with increasing GeO₂ content. Our results clearly reveal an enhancement of the Brillouin gain efficiency in heavily GeO2 core-doped fibers compared to that of standard silica single-mode fibers. The Brillouin frequency shift (BFS) can be tuned over more than 4 GHz with a strong decrease from 15.95 GHz (SMF-28) down to 11.87 GHz (ultra-high doping level, 75 mol.% GeO₂). At the same time, the spectral width of the Brillouin gain widens strongly up to 69.7 MHz, with the increase of the GeO₂ core content. Next, we select the most suitable fiber to form our 1-µm BFL combined with a phase-locking loop scheme to ensure stable and mode-hop free operation. Owing to the intrinsic properties of SBS, a Stokes lasing threshold and narrow-linewidth of 140 mW and 50 Hz respectively, have been obtained for a 15-m-long cavity. Finally, we show a frequency noise reduction of the lasing Stokes component, compared to that of the initial pump laser source.

2. EXPERIMENTAL SETUP

Figure 1 depicts the complete experimental setup used for both implementation and characterization of our stabilized BFL with a standard non-resonant pumping configuration [4]. An amplified narrow-linewidth continuous-wave laser tunable from 1.039 to 1.075 μ m (Toptica DLC-PRO-025563) was used as a



Fig. 1. Experimental setup of BFL cavity (blue rectangle) combined with a phase-locked stabilization loop diagram (red rectangle). A self-delayed heterodyne detection (green rectangle) is used here for coherence characterization of the laser. PC: Polarization controller, OC: Optical circulator, FC: Fiber coupler, FUT: Fiber under test, RFA: Radio-frequency amplifier, ESA: Electrical spectrum analyzer, PD: Photodiode, LO: Local oscillator, FPGA: Field-programmable gate array, AOM: Acousto-optic modulator.

pump laser. This pump laser was then split into two parts. The 102 66 first part is injected into the highly-nonlinear germanosilicate 67 103 fiber (FUT: fiber under test) that forms the cavity using an op-104 68 tical circulator (OC). A 90:10 fiber tap coupler was inserted to 105 69 extract and characterize the BFL signal while the remaining 90% 106 70 of the Stokes wave was fed back into the passive fiber ring cavity. 107 71 Note that fiber components used here are made of high-index 108 72 core single-mode fiber (HI-1060). The Stokes wave makes mul- 109 73 tiple roundtrips, while the pump laser, which circulates in the 110 74 opposite direction, is isolated by the OC. The second part of 111 75 the laser is used to create a beatnote with the BFL. This beat- 112 76 note is stabilized to an external oscillator via a phase-locking 113 77 loop (PLL) that feeds back the laser wavelength [17, 18]. This 114 78 suppresses the thermal drift of our fiber cavity relative to the 115 79 pump laser. The detected 13.36 GHz beat note signal between 116 80 the pump laser and the Stokes laser, which corresponds to the 81 117 82 Brillouin frequency shift, is then mixed with a Local Oscillator 118 signal provided by an electrical synthesizer whose frequency is 83 119 set at 13.325 GHz. The mixer output around 33 MHz is fed into a 120 84 field-programmable gate array (FPGA)-based digital frequency 121 85 counter and proportional-integrator active digital filter [19]. Fi-86 nally, the feedback loop is closed by applying the FPGA output 123 87 signal to the laser diode current. An electrical spectrum analyzer 124 88 (ESA) is used here to carefully check the single frequency opera-89 tion of the BFL. The rest of the BFL output is then split into two 126 90 paths. The first part is sent into an optical spectrum analyzer 127 91 (OSA, Yokogawa AQ6370) with a resolution of 4 GHz for spec- 128 92 tral characterization of stokes lasing. The second part is sent to 129 93 a delayed self-heterodyne detection (SHD) setup to measure the 94 130 coherence properties of the BFL. Finally, a heterodyne detection 95 131 based on a beatnote between an auxiliary laser operating around 132 96 1.064 μ m and our BFL has been performed, in order to validate 133 97 our coherence measurements independently. 98

3. BRILLOUIN SCATTERING CHARACTERIZATION

In order to optimize our fiber cavity, we present the character ized SBS properties of three germanosilicate fibers compatible
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for an all-fiber configuration with standard single-mode fiber at 1 μ m, namely a standard fiber (3.6% mol, SMF-28), a highly nonlinear fiber from Sumitomo Electrics (21% mol, HNLF-1), and a heavily doped-core fiber (75% mol, HNLF-2) from the Fiber Optic Research Center (FORC, Russia).

We measured the experimental SBS threshold (P_{th}) at 1.06 μ m pump wavelength in two long fiber samples available, namely a 1.5-km-long segment of SMF-28 fiber and a 0.38-km-long segment of HNLF-1 fiber. The backscattered Stokes wave power as a function of the injected pump power, are shown in Fig. 2(a). In both cases, we first observe the spontaneous Brillouin scattering regime, where the Stokes power increases linearly with the pump power, followed by a transition to the stimulated regime, characterized by a faster increase. We define the Brillouin threshold power as the input power for which the backscattered power reaches 1% of the injected pump power [20], which is equal to 17.2 dBm in the SMF-28 fiber and 15 dBm in the HNLF-1 fiber. These experimental data are very close to the analyticallyestimated single-pass SBS threshold values (16.55 and 16.86 dBm for SMF-28 and HNLF-1 fiber respectively, see Eq. 1). A clear difference of 2.2 dB is experimentally observed, while the first sample (SMF-28) is about 4 times longer than the second one (HNLF-1) showing a better opto-acoustic coupling efficiency in the latter case [21]. It worth noting that the Brillouin threshold could not be reached experimentally in the HNLF-2 fiber (see Fig. 2 (a)). In fact, the short fiber length (20 m), implies a high threshold power, which is beyond our maximum available pump power of 250 mW (23.97 dBm, recorded after the port 2 of the optical circulator) at 1 µm wavelength. However, the theoretical single-pass Brillouin threshold value of this specific HNLF-2 fiber was estimated at 26.3 dBm (426.58 mW) based on the following equation [1, 22, 23]:

$$P_{\rm th} = \frac{21A_{\rm eff}K}{g_B L_{\rm eff}},\tag{1}$$

where, K = 1.5 is the polarization factor, $L_{\text{eff}} = (1 - e^{-\alpha L})/\alpha$ the effective fiber length, α the linear fiber loss, A_{eff} the effective mode area, and g_B is the Brillouin gain coefficient.



Fig. 2. (a) Experimental measurement backscattered Stokes powers as a function of the injected pump power for standard singlemode silica optical fiber (SMF-28) and high nonlinear silica fibers (HNLF-1, 21 mol. % GeO₂ and HNLF-2, 75 mol. % GeO₂). (b) Experimental Brillouin spectra measured at 1.06 µm in three single-mode germanosilicate core fibers namely SMF-28 (21 mol. % GeO₂), HNLF-1 (21 mol. % GeO₂) and HNLF-2 (75 mol. % GeO₂). Inset: Example of experimental spontaneous backward Brillouin spectrum (blue curve) measured in HNLF-1 fiber and corresponding fit with a Lorentzian curve. (c) SBS gain efficiency as a function of GeO₂ core content.

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The BFS ν_B and the Brillouin gain bandwidth $\Delta \nu_B$ were exper-137 imentally measured at 1.06 µm in the spontaneous regime (well 138 below the Brillouin critical power threshold) by using a standard 139 heterodyne detection technique, as described in Ref [24]. We 140 characterized our three distinct germanosilicate core fibers as 141 a function of the GeO₂ content (SMF-28: green line; HNLF-1: 142 blue line; HNLF-2: red line). As can be clearly seen in Fig. 2 (b), 143 144 the BFS strongly reduces from 15.95 GHz down to 11.87 GHz when increasing the GeO₂ content in the fiber core. Indeed, the 145 GeO₂-doping level strongly changes the elastic properties such 146 as the phonon velocity, Young's modulus, and the mass density 147 [25]. As a result, the longitudinal acoustic velocity decreases 148 sharply, which affects the BFS owing to the phase matching rela-149 tionship [1]. The Brillouin spectral linewidth, obtained with a 150 Lorentzian fit, as shown in the inset of Fig. 2 (b), also increases 15 from 20.5 MHz up to 69.7 MHz with doping, due to the drastic 152 reduction of the acoustic phonon lifetime [26]. 153

Next, the Brillouin gain coefficient, which depends on pump-176 154 ing wavelength, index guiding features, and material properties, 155 of the germanosilicate fibers under test can be estimated by 156 178 means the following equation [1, 23]: 157 179

$$g_B = \frac{2\pi n_{\rm eff}^7 p_{12}^2}{c\lambda^2 \rho v_A \Delta v_B},$$
 (2) ¹⁸⁰

where *c* is the velocity of light, p_{12} is the photo-elastic constant 158 184 159 of the glass material, ρ is the material density, and Δv_B is the 185 full width at half-maximum of the Brillouin gain spectrum. The $_{\rm 186}$ 160 spectral width Δv_B is related to the phonon lifetime $T_B = \frac{1}{\pi \Delta v_B}$. ¹⁸⁷ 161 Taking into account the effective mode area of the three dis-162 188 tinct fibers, the estimated SBS gain efficiency (g_B/A_{eff}) increases 189 163 strongly from $0.59 \text{ W}^{-1} \text{ m}^{-1}$ (SMF-28 fiber) up to $4.62 \text{ W}^{-1} \text{ m}^{-1}$ 164 (HNLF-2 fiber) at 1-µm as shown in Fig. 2 (c), indicating better 165 opto-acoustic confinement in these fibers [21]. Indeed, increas- 192 166 ing the core doping level significantly reduces the effective mode 193 167 area Aeff, which increases the Brillouin gain into the fiber. Ta- 194 168 ble 1 summarizes both opto-geometric and SBS characterization 195 169 results for all fiber samples under test. Taking into account the 196 170 SBS characteristics and opto-geometric properties of the fibers 197 171 studied for their integration with single-mode fiber components 198 172 operating in the near 1-µm spectral region, it appears that the 199 173 HNLF-1 fiber with 21% mol GeO2 is the most suitable for build- 200 174 ing a Brillouin laser. 201 175

Table 1. SBS characterization of three distinct GeO₂-doped core fibers at 1 µm wavelength

Fiber (GeO ₂ mol %)	SMF-28	HNLF-1	HNLF-2
Core diameter, ϕ (µm)	8.2	3.6	2.3
Fiber loss, α (dB km ⁻¹)	1.1	4.8	100
Effective area, $A_{\rm eff}$ (μm^2)	55	8.5	3.5
Fiber length, L (m)	1500	380	20
SBS freq. shift, ν_B (GHz)	15.95	13.36	11.87
SBS bandwidth, Δv_B (MHz)	20.5	48.7	69.7
SBS gain, $\frac{g_B}{A_{\text{eff}}}$ (W ⁻¹ m ⁻¹)	0.59	1.85	4.62
SBS threshold, $P_{\rm th}$ (dBm)	17.2 (16.55*)	15 (16.86*)	26.3*

* Analytically-estimated single-pass SBS threshold

4. BRILLOUIN LASER RESULTS

Next, we implemented the BFL cavity with a 15-m-long segment of HNLF-1 fiber. The fiber length was chosen as a trade-off between the gain-loss balance in the ring cavity and the number of cavity modes. The cavity finesse *f* was estimated to be around 3.3 based on the total cavity losses of 3 dB. The cavity free spectral range (FSR) is calculated to be 12.8 MHz based on the total cavity length.

We then characterized the output signal of the corresponding BFL. In Fig. 3, we show the Stokes power as a function of the input pump power for HNLF-1 fiber with lasing threshold of 140 mW. The inset of figure 3 shows the evolution of the BFL spectra operating around 1 µm, while increasing the pump power from 30 to 200 mW. Note that the pump power is measured at port 1 of the OC. Below the Stokes lasing operation, we clearly see the presence of reflected pump mainly coming from both Fresnel reflections and Rayleigh scattering. By increasing the injected power, the Stokes lasing occurs (blue spectrum) as an upper wavelength shift of 50 pm that matches the SBS frequency and thus confirms that the Brillouin gain is strong enough to compensate the ring cavity losses beyond the threshold. For higher input powers, the first Stokes wave grows significantly and can generate a second-order Stokes wave.

Fig. 4 (a) shows the spectrogram of the beatnote frequency between the Brillouin laser and the pump source, when the PLL is both disabled and active. Without locking, the thermal drift



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Fig. 3. Stokes lasing threshold measurement of HNLF-1 (15-m long segment, blue circle). Inset: Experimental BFL optical spectra dynamics with the HNLF-1 fiber by varying injected pump power.

of the fiber ring cavity relative to pump laser leads to rapid 261 202 mode hopping, multimode and unstable emission of Stokes las-203 262 ing frequency. Note that mode hopping is clearly visible when 263 204 the Stokes frequency emission switches from one longitudinal 264 205 mode to another, stepping by one cavity FSR. Activating the 265 206 PLL to stabilize the beat note maintains a stable single-frequency 207 266 Brillouin laser without mode hopping. In Fig. 4 (b), we show 267 208 the beating signal between the pump source and BFL recorded 209 268 210 with 51 kHz of resolution bandwidth with an excellent coherent 269 single-frequency lasing emission. We underline that, in our ex-211 periment, no mode hopping was observed at any injected pump 271 212 power during the measurement [17]. We further investigated 272 213 the coherence properties of our BFL. The linewidth of a BFL can 273 214 be theoretically estimated using the following equation [27]: 215 274

$$\Delta \nu_{\rm BFL} = \frac{\Delta \nu_{\rm Pump}}{(1 + \frac{\pi \Delta \nu_B}{\frac{c}{nL} \ln(\frac{1}{R})})^2}$$
(3) 276

where Δv_{BFL} , Δv_{Pump} , Δv_B , c, n, L and R are the linewidths of the 279 216 Brillouin and pump lasers, the SBS linewidth, the speed of light, 280 217 the refractive index, the fiber length, and the cavity feedback 281 218 219 parameter, respectively. Using Eq. (3), we can expect a 23 dB nar- 282 rowing of the BFL linewidth compared to the pump laser. The 220 phase and frequency noises of both BFL and pump laser were 221 284 also characterized afterward, based on the SHD interferometer 285 222 and a digital RF coherent receiver [28]. A short delay line of 7.32 286 223 μs (corresponding to the fiber length of 1.5-km) which is less than 224 287 the coherence time of the laser was here used. In this configura- 288 225 tion, the system operates in coherent mode [29, 30] and the phase 289 226 fluctuations of the laser were measured by recording the power 290 227 spectral density (PSD) using RF analyzer. The frequency noises 291 228 of the pump laser and HNLF-1 BFL were added on the same 229 plot as described in Fig. 4 (c). Importantly, the interferometer 230 292 frequency response on the phase noise PSD measurements was 231 removed by using a simple numerical filtering approach devel- 293 232 oped in Ref [31]. The measurement noise floor was characterized 294 233 by measuring the frequency noise of the voltage-controlled oscil- 295 234 lator driving the AOM (black curve). Across the measurement 296 235 range, the BFL frequency noise (blue curve) exhibits a stark re- 297 236 duction compared to that of the pump laser (red curve), which 298 237 reflects the typical linewidth narrowing of the Brillouin effect. 299 238 Note that the pump laser noise was measured with the PLL 300 239 disabled. To estimate the integrated linewidth of the BFL and 301 240

pump laser from the noise measurements, we used the common beta-separation line criterion [32]. This line separates high and low modulation index areas in the frequency noise PSD, which distinguishes contributions to the linewidth versus the wings of the RF line shape. It worth noting that, the beta separation line is an integrated linewidth method that accounts for the technical noise. In that case, it is defined over the integration time of the measurement, which was 10 ms corresponding to the lowest Fourier frequency of 100 Hz. An integrated linewidth of \sim 10 kHz was obtained for the initial pump laser. This value was confirmed by another measurement carried out with a 50-km fiber for direct measurement of the spectral width of the pump laser, which provided a value of 15-kHz. In the case of our BFL output, the intersection between the beta-separation line and the Stokes laser frequency noise yields a narrower integrated linewidth of 1 kHz. Note that using Eq. 1, the narrowed BFL linewidth was expected to be about 50 Hz. The discrepancy between our measurement and theoretical prediction of BFL linewidth can be ascribed to the additional technical noise arising from the mechanical fluctuations [27, 33, 34] of our system, which is not isolated nor packaged, as well as the coupling fluctuations of the laser pump power, which is injected using free space optics before the fiber coupler FC1. We believe the fundamental thermal noise of the resonator [33, 35] is not a limiting effect in our case owing to the large size of the cavity.

Another way of characterizing the laser bandwidth, which is more insensitive to technical fluctuations, is to take into account only the background white frequency noise, which yields an intrinsic (Lorentzian) linewidth. The white frequency noise of our Brillouin laser is at a level of $0.38 \text{ Hz}^2/\text{Hz}$ which yields a intrinsic (Lorentzian) linewidth of 1.19 Hz [8, 34, 36]. The white noise floor of the pump laser is $700 \,\text{Hz}^2/\text{Hz}$ corresponding to a intrinsic linewidth of 2.2 kHz. These noise levels thus yield a 32 dB reduction of the frequency noise. This reduction factor is sizably larger than the theoretically predicted value. We can ascribe this phenomenon to the presence of the feedback loop, which further trims the pump laser noise and enhances the narrowing [37]. The fundamental limit of the Brillouin laser linewidth (see eq. (11) in [34], also used in [10]) is estimated at 28 mHz, which suggests that our system is still limited by the pump noise.

We used the low-noise features of our BFL laser as an optical frequency reference to characterize an auxiliary laser operating around 1.06 μ m (RIO 0075-5-08-1, 6-kHz linewidth). To this end, an optical beat-note signal between the two lasers was generated, as shown in Fig. 4 (d), and its phase noise was measured and compared with the SHD measurement of the auxiliary laser. Both measurements show a very similar level and evolution of the frequency noise, indicating the heterodyne system validity and that the noise of our BFL is lower and thus does not limit the auxiliary laser characterization.

5. CONCLUSION

To conclude, a stabilized single-frequency Brillouin narrowlinewidth laser has been demonstrated at 1.06 µm wavelength using a short length of highly GeO₂-doped-core silica fiber. The SBS characterization shows a strong enhancement of the Brillouin gain efficiency in such fibers, thus enabling a BFL threshold of 140 mW with our passive ring cavity, while the resulting BFL linewidth is found to be sub-kHz. Moreover, the significant phase noise reduction of the lasing Stokes component, compared to that of the initial pump laser, is also confirmed. Our mode-



Fig. 4. (a) Spectrogram of relative Stokes laser recorded with 51 kHz resolution bandwidth. (b) Excellent coherent single frequency Stokes emission in phase-locked configuration. (c) Frequency noise of the voltage-controlled reference oscillator (VCO) of AOM, pump source, BFL and auxiliary laser source. The β -separation (solid line, in yellow) shows the intersection with the frequency noise curves, useful for estimating the integrated linewidth. (d) Comparison of Stokes laser frequency noise with auxiliary laser and beat-note noise.

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hop free BFL is tunable over the full wavelength range of the 343 302 303 pump laser (here, nearly 40 nm). We believe that this low-noise, 344 304 narrow-linewidth BFL is a promising laser source to provide 345 346 low-noise reference laser in the spectral region near 1-µm us-305 ing affordable fiber components and to generate Brillouin-Kerr 306 348 frequency comb [38]. 30 349

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