On the Use of Brillouin Scattering to Evaluate Quantum Conversion Efficiency in Yb-doped Optical Fibers

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Abstract—A method, based on Brillouin scattering, to evaluate the quantum conversion efficiency (QCE) in Yb-doped optical fibers is designed and tested. An adapted version of the heterodyne approach to measuring the Brillouin spectrum is first used to precisely quantify the temperature change of the fiber upon pumping. Next, a theoretical model based on the thermal conduction equation is constructed in order to simulate the temperature change assuming a QCE of one. Lastly, the QCE value of the fiber can be determined by comparing the experimental and simulation results. Importantly, the analysis can provide insight into the origin of thermal energy in a fiber. Serving in the proof-of-concept measurement, a commercial, lightly Yb-doped fiber is determined to have a QCE of 99.07%. Finally, this result is compared with slope efficiency measurements from a linear cavity laser using the same fiber as the active medium. Excellent agreement between the two measurements demonstrates the feasibility of the approach, with greater accuracy afforded by the Brillouin-based measurement. The proposed method is particularly useful for optical fiber optimization in high-power fiber laser and amplifier applications. It can also be valuable as a sensitive temperature probe in the study of anti-Stokes fluorescence cooling in optical fibers.

Index Terms—Brillouin scattering, optical fibers, quantum conversion efficiency, thermal effects.

I. INTRODUCTION

OVER the past two decades, fiber laser systems have developed expeditiously in several different wavelength windows. Higher powers and greater efficiencies are pursued in all of them, targeting a wide range of applications [1]–[7]. However, thermal effects usually serve as a limiting factor to further power scaling, especially in Yb-doped fiber lasers [8]. To achieve improved thermal management, a straightforward active solution is to introduce advanced water or air cooling systems [9]–[12] so that heat is removed more efficiently. However, this inevitably induces thermal gradients in the fiber, adding additional temporal and spectral noise to the laser output [13].

Therefore, other passive solutions are desired. One approach is to reduce the intrinsic thermal energy generation in fiber lasers by lowering the quantum defect (QD) in the system, which can be achieved by either building new pumps at longer wavelengths to support tandem pumping [3], [8], [14], [15], or shortening the lasing wavelength by a selection of new host glasses [16]–[20]. Another approach, known as anti-Stokes fluorescence (ASF) cooling [21], can also provide improved thermal management. When optically excited at a wavelength that is longer than the fiber average emission wavelength, phonons are extracted from the fiber through the production of spontaneous emission, leading to the possibility of self-cooled radiation-balanced fiber lasers [22].

The passive above approaches offer better management of thermal energy by harnessing radiative processes in fibers. Meanwhile, thermal energy can still be generated via nonradiative processes which can easily become a dominant factor in deteriorated system performance. For example, in Ref [18] where the QD is reduced to less than 1%, nonradiative processes serve as one of the limiting factors to achieving higher slope efficiencies. As another example, it is discussed in Refs [23]–[25] that heat generation from nonradiative processes strongly counteracts ASF cooling. As a matter of fact, this is one of the reasons long preventing the demonstration of laser cooling in silica glass [24]–[26]. Therefore, to optimize fiber design for high-power laser applications, it is meaningful and necessary to evaluate the quantum conversion efficiency (QCE) of the fiber, which is defined to be the fraction of pump photons that undergo a desired radiative process. Ideally, QCE should equal to 1 in the quantum limit, meaning that for every photon provided for pumping, there will always be a photon emitted as signal. This excludes, of course, cases such as pumping into the $^3H_4$ level of Ti$^{3+}$ near 790 nm, which can lead, through cross-relaxation processes, to the emission of more than one signal photon near 2 μm for each absorbed pump photon [3]. However, nonradiative processes originating from impurities (such as transition metals, undesirable rare-earth ions, OH $^-$, etc.) or quenching [24]–[26] will make the QCE less than one and adversely influence laser or amplifier efficiency, as discussed above.

To evaluate the QCE of a fiber, one can first precisely measure the temperature change of the fiber when the pump light is injected. Then, the QCE of the fiber can be deduced from the temperature difference between the measurement and a model that considers a QCE of 100%. This method will be discussed in more detail in the next section.
detail in Section 3B and is only valid when two requirements are met. First, those pump photons that undergo nonradiative processes contribute to thermal energy through fast phonon processes. This is generally a valid assumption with Yb$^{3+}$ as suggested by Refs. [23]–[26]. Second, the fiber should have minimum conductive and convective thermal energy transfer to extrinsic materials, such as mechanical supports for the fiber, so that the temperature of the fiber itself is accurately measured. Fortunately, this is the same requirement as found in ASF cooling measurements and many methods can therefore be found in the literature that address this latter requirement [24]–[31]. For example, mounts made of thin silica filaments, onto which samples are placed, are used in Refs [28]–[31]. Physical contact between the test fiber and the sensor with extremely low absorbance is created with the aid of isopropanol in Refs [24]–[26]. As for temperature sensing, a variety of methods are used, including thermal cameras [28], [29], [31], temperature-dependent Yb$^{3+}$ emission [30], and slow-light, ultra-high resolution FBGs [24]–[27], each exhibiting great ability to quantify the temperature in the given configuration. In terms of advantages, some methods possess high temperature resolution (0.3 mK [27]) or fast response time (50 ms [29]), while others exhibit high dynamic range (>100 K [31]) or convenient all-fiber setup without free-space coupling components [24]–[26].

These various configurations also have their own drawbacks. First, where free-space components are used [28]–[31], there is additional time needed for alignment and careful control of any mechanical instability that may misalign the fiber (such as the air flow when pumping down a vacuum chamber) and introduce additional coupling loss to the system. Second, for those methods using thermal cameras [28], [29], [31], the sample dimensions are on the order of 10 millimeters, nearly 100 times greater than a standard 125 μm fiber. Therefore, it may be challenging for the thermal camera to image a much smaller fiber, unless a magnifying system is constructed [32], adding considerable cost and complexity to the measurement. Third, the dynamic range is relatively small in the methods described in Refs [24]–[27], which is only 14 K. Although it can be increased with a more powerful laser source, a range of 100 K or more is more desirable, as this is a temperature change that can be reached in high-power lasers [33]. Therefore, a simple, all-fiber (no free space coupling) and wide-temperature range method with careful control of the conductive and convective thermal transfer is desired. In this work, such a method, based on Brillouin scattering, is designed and a proof-of-concept test is presented, in which the system is used to estimate the QCE of a commercial Yb-doped fiber. This result is then compared with slope efficiency measurements in a linear laser constructed from the same fiber. The results demonstrate the feasibility of the approach, which also is expected to be useful in the study of ASF cooling.

II. EXPERIMENTAL SETUP

Jeong et al. [34] demonstrated the use of a Brillouin optical time domain analysis (BOTDA) approach to measuring the axial temperature profile (with 0.5 m resolution) in a long Yb-doped fiber laser. One apparent goal of that work was to study the effect of a non-uniform temperature distribution on the relative Brillouin gain in the core of the fiber. Rather than focus on a temperature distribution, the main interest here is the development of a system with high temperature resolution, and one where the measurement can be single ended, rather than needing access to both fiber ends as is required in BOTDA. The need for this will become apparent with the abundance of light leakage from the output end of the test fiber, which need not be rigorously managed in a single-ended measurement. Fig. 1 shows the schematics of the experimental setup, which is an adapted version of the heterodyne approach commonly used for the characterization of the spontaneous Brillouin scattering spectrum [35]–[41]. A narrow-linewidth (85 kHz) laser signal at 1534 nm, amplified by an erbium-doped fiber amplifier (EDFA), is passed through a circulator and launched into Port 1 of a wavelength division multiplexer (WDM). This wavelength serves as the pump for the Brillouin scattering process (“Brillouin pump”). A second pump laser, which is used to excite the Yb$^{3+}$ ion (“Yb pump”), is directly coupled into Port 2 of the WDM. Then the combined signal (Ports 1 + 2) is injected into the test fiber, which is placed on top of a silica aerogel tile inside an acrylic vacuum chamber. The thermal conductivity of the aerogel tile is as small as 0.023 W/mK so that conductive heat transfer is extremely low. Meanwhile, through the use of the vacuum chamber, both conductive and convective heat transfer via air are largely eliminated. In this way, the temperature change of the fiber is larger compared to performing the same experiment at ambient pressure, enhancing the accuracy in determining small temperature variations. To perform heterodyning with a minimum number of components, a simple straight-cleave was made at the end of the test fiber to provide the local oscillator (LO) signal. Then, the LO signal, together with the back-reflected Brillouin signal, are collected from Port 3 of the circulator through an optical filter (Bandpass @1534 ± 0.75 nm) and amplified by another EDFA. Finally, the beat signal between the LO and Brillouin signal is detected by a fast PiN photodetector and displayed on an electrical spectrum analyzer.

The Brillouin frequency shift is known to be a function of temperature because the material acoustic velocity increases with increasing temperature in most silica glasses [5]. The approach here is to first measure the Brillouin spectrum at
equilibrium temperatures as calibration, with no Yb pump power provided. More details on this are provided in the next section. Then, Yb pump laser power is varied, and any change in the temperature of the test fiber can be characterized through the frequency shift of the Brillouin signal. Since the measurement does not require any physical contact with the fiber (aside from the low-thermal-conductivity aerogel) and all the components are fiber-coupled, it forms a simple, all-fiber, and contactless platform for temperature characterization, which will be tested and discussed in the next section. As will be shown, since the system integrates the Brillouin spectrum of the whole fiber length, pumping is adjusted in order to create uniform inversion (in other words a uniform temperature distribution) throughout the length of test fiber. Finally, it is necessary to point out that the measurement range of the setup is not limited, as long as calibration can first be done at such temperatures, enabling the possibility of high-temperature measurements if required.

III. FUNCTIONALITY TESTING

In this section, the functionality of the proposed setup is investigated using a commercial Yb-doped fiber (National Optics Institute (INO), Yb-103). As will be shown, this enables a direct comparison with a linear laser experiment to understand the viability of measuring the QCE using the Brillouin apparatus. Theoretical models are also constructed to assist the analysis.

A. Test Fiber Characterization

First, several basic parameters of the test fiber are quantified. These measurements have been used as standard tools for these authors in characterizing other optical fibers. Therefore, only a brief discussion on the measurement procedures is provided below, with relevant references provided alongside should more details be desired.

The refractive index profile (RIP) was measured, as a service (Interfiber Analysis), at 978 nm using a form of spatially resolved Fourier Transform spectroscopy [42]. The result near the core is provided in Fig. 2(a), from which a graded-index profile with a core diameter of 4.7 μm is observed.

In order to measure the absorption spectrum, a 1-cm segment of the test fiber was spliced between two passive fibers and the spectrum of a white light source was measured both before and after propagating through the test fiber. The absorption spectrum α(λ) was then determined by the difference between the two measurements. In particular, the small signal absorption at the zero phonon line is determined to be 34 dB/m. Considering an absorption cross section σa(λ) is calculated from \( \sigma_a(\lambda) = \frac{\alpha(\lambda)}{\Gamma \rho} \), where \( \Gamma \) is the mode overlap with the Yb\(^{3+}\). The result is provided in Eq. (1).

\[
\Sigma = \frac{\int_0^\infty I(\lambda) \lambda d\lambda}{\int_0^\infty I(\lambda) d\lambda}
\]

For the fluorescence lifetime (τ) measurement, a 1-mm segment of fiber was spliced to the pigtail end of a 976.5 nm laser diode pump, whose power was pulsed with a period of 6.5 ms and a duty cycle of 1%. The output signal from the fiber was then filtered, attenuated, and detected by an avalanche photodiode. The detected signal was displayed on an oscilloscope, from which the fluorescence lifetime of the fiber can be determined.
to be 760 μs [20]. With the measured emission spectrum and fluorescence lifetime, the emission cross section (σ_e) can be calculated using the Füchtbauer-Ladenburg formula [5], [44], [45]

$$\sigma_e(\lambda) = \frac{\lambda^5}{8\pi n^2 c^2} \int_0^\infty I(\lambda) \frac{d\lambda}{\lambda^2}$$  \hspace{1cm} (2)

where c is the speed of light in vacuum and n is the refractive index of the fiber. The calculated result for the test fiber is shown in Fig. 2(b). The emission spectrum is noisy due to weak spontaneous emission resulting from the low Yb^{3+} concentration in the fiber.

Finally, the Brillouin spectroscopy is thermally calibrated. Using the experimental setup in Fig. 1, with the test fiber placed inside a heated water bath instead of the vacuum chamber, the Brillouin signal is measured as a function of temperature with no Yb pump power present. The result is shown in Fig. 2(c), indicating a linear Brillouin frequency temperature dependence of 1.075 MHz/°C. This value will be used to convert the measured frequency shift to corresponding temperature change in Section 3B. For the convenience of the reader, some key parameters of the test fiber are summarized in Table I.

### B. Experimental Results and Analysis

Next, a 1.4 m sample of the test fiber is spliced into the system and placed on top of the aerogel tile inside the vacuum chamber. The fiber length is chosen to be long enough to provide sufficient Brillouin scattering for detection with high signal-to-noise ratio, but not so long so that less than 1 W of pump power is required to achieve a uniform temperature distribution. In our absorbed power per length characterization, there was significant pump leakage from the fiber, guaranteeing that pumping was in the saturated regime, which further gives rise to a uniform distribution of temperature. The buffer of the test fiber is stripped off mechanically with a standard fiber stripper to avoid absorptive heating in that layer. The Yb^{3+} pump laser is chosen to be a single-mode fiber-coupled laser diode with a wavelength (λ_p = 976.5 nm) that is shorter than the average emission wavelength (λ = 1009.3 nm). As a result, phonons will be generated via Stokes processes when fluorescence is produced, and a temperature increase is therefore expected. Then, after pumping down the vacuum chamber, Brillouin signals of the fiber are measured as a function of absorbed pump power (input power minus power leakage at the end) and relative frequency shifts are recorded. Using the Brillouin signal temperature dependence calibration from above, the temperature change of the fiber as function of the absorbed pump power can be determined and is shown as triangles in Fig. 3(a).

Next, a theoretical model is constructed to simulate the thermal distribution of the fiber considering a QCE of 1. The radial thermal distribution  \( T(r) \) is governed by thermal conduction equation [33]

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T(r)}{\partial r} \right) = -\frac{Q}{k}$$  \hspace{1cm} (3)

where r is the radial coordinate, Q the heat power density (W/m^3), and k the thermal conductivity (W/mK). In the fiber, specifically, since the buffer is removed in the setup, only two regions (core and cladding) are considered in the model. The heat power density in the core is defined as  \( Q_1 \), and the thermal conductivities of the core (k_1) and the cladding (k_2) are assumed to be that of silica (1.38 W/mK [33]). Applying boundary conditions, the radial temperature distribution in the core  \( T_1(r) \)

\[ \begin{array}{c}
T_1(0) = T_0 \\
\frac{\partial T_1(r)}{\partial r} \bigg|_{r=0} = 0 \\
T_1(R) = T_2 \\
\frac{\partial T_2(r)}{\partial r} \bigg|_{r=R} = 0 \\
\end{array} \]

\[ T_2(R) = T(x) \]

where T_0 is the ambient temperature, T_2 the core-cladding interface temperature, R the radius of the fiber, and x the axial coordinate.
and cladding $T_2(r)$ can be determined to be [33]

$$T_1(r) = T_0 - \frac{Q_1 r^2}{4 k_1} \cdots \cdots (0 < r < r_{core})$$

(4)

$$T_2(r) = T_0 - \frac{Q_1 r_{core}^2}{4 k_1} - \frac{Q_1 r_{core}^2}{2 k_2} \ln \left( \frac{r_{core}}{r} \right) \cdots \cdots (r_{core} < r < r_{clad})$$

(5)

where $r_{core}$ is the core radius, $r_{clad}$ is the cladding radius, and $T_0$ is the temperature at the core center and is expressed by

$$T_0 = T_a + \frac{Q_1 r_{core}^2}{2 h r_{clad}} + \frac{Q_1 r_{core}^2}{4 k_1} + \frac{Q_1 r_{core}^2}{2 k_2} \ln \left( \frac{r_{clad}}{r_{core}} \right)$$

(6)

in which $T_a$ is the ambient temperature and $h$ the heat transfer coefficient. Considering QCE = 1, heat is only generated by the quantum defect of the system. Therefore, $Q_1$ is calculated by

$$Q_1 = \frac{P_{abs}}{L \pi r_{core}^2} \times QD$$

(7)

where $P_{abs}$ represents the absorbed pump power, $L$ represents the fiber length, and the quantum defect ($QD$) is defined by $1 - \frac{2}{\varepsilon}$. Since the fiber is placed on an aerogel tile inside the vacuum chamber, only radiative heat transfer is considered with its coefficient calculated from [46]

$$h = \frac{\varepsilon \sigma_b (T_2(r_{clad})^4 - T_a^4)}{T_2(r_{clad}) - T_a}$$

(8)

where $\varepsilon = 0.85$ is the emissivity and $\sigma_b$ the Stefan-Boltzmann constant.

Using the model described above, the radial temperature distributions in the fiber at different absorbed pump powers are calculated, with an example shown in Fig. 3(b). In this specific case (112.1 mW absorbed pump power), the ambient temperature, $T_a$, is 298 K and the temperature at the core center is 1.352 K above $T_a$, whereas the temperature variation from the core center to the cladding edge is less than 1.2 mK. Therefore, the temperature variation can be neglected, and the temperature of the core center is taken to be the fiber temperature. As a matter of fact, it is from within the core that the Brillouin signal originates, making this a valid and appropriate simplification. Finally, the temperature change as a function of absorbed pump power is calculated and shown by the squares in Fig. 3(a).

A difference between the experimental result and the model is observed. This is due to the assumption of a 100% QCE, which is not necessarily the case in the fiber. As described above, the presence of nonradiative processes will generate additional thermal energy. Taking these nonradiative processes into consideration, the corrected heat power density becomes

$$Q_1 = \frac{P_{abs}}{L \pi r_{core}^2} \times QCE \times QD + \frac{P_{abs}}{L \pi r_{core}^2}(1 - QCE)$$

(9)

where the first term represents quantum defect heating that is reduced by the QCE factor, and the second term is heating due to nonradiative processes. Since the temperature increase has a linear relation with heat power density, as indicated by

Eqns. (4)–(6), the experimentally measured ($\Delta T_a$) and the modeled ($\Delta T_m$) temperature changes are related by

$$\frac{\Delta T_a}{\Delta T_m} = \frac{Q_1}{Q_1} = 1 - QCE(1 - QD)$$

(10)

In which the only unknown is QCE. Therefore, the QCEs at the different absorbed pump powers can be determined and the results are shown in Fig. 3(a) as stars. The average QCE is determined to be 99.07%, with only small variations between measurements, indicating a high-quality fiber with very weak nonradiative processes and a power-independent QCE. This can be explained as follows. Given the low Yb$^{3+}$ concentration in the fiber, no concentration quenching effects are expected [47]. As such, the nonradiative heating likely only comes from impurities, which is linearly proportional to pump power (or in other words, via unsaturable absorption). If the fiber does suffer from concentration quenching, the same measurement will possibly lead to a power-dependent QCE, giving insight into how quenching effects evolve with increasing pump power. However, this subject is beyond the scope of this paper and will be discussed elsewhere.

C. Comparison With Lasing Measurement

In this section, a linear cavity laser with the test fiber as the gain medium is constructed to confirm the QCE value calculated in the last section. The experimental setup is shown in Fig. 4. The pump laser is identical to that used in Section 3B. The cavity is constructed by a fiber Bragg grating (FBG, 99.1% reflectivity at 1017.15 nm) and a straight cleave at the laser output end, which relies on a Fresnel reflection (~3.4%). An isolator is placed between the pump and the cavity to prevent reflections from the cavity destabilizing the pump wavelength.

To achieve efficient laser operation, the active fiber (test fiber) length is a critical parameter in the system. A length that is too short will lead to incomplete pump absorption, resulting in a large portion of pump power leaking out and being wasted. A length that is too long will lead to signal reabsorption and stronger amplified emission (ASE), resulting in a reduced slope efficiency. Therefore, to find the optimized active fiber length for efficient lasing, test fiber segments ranging from 5 m to 8 m were spliced into the cavity and the corresponding output spectra were recorded with an optical spectrum analyzer. The fiber is loosely coiled to a 50-cm diameter (negligible bending loss) with its buffer remaining on. A summary is shown in Fig. 5. The pump power when recording these spectra was fixed at 490 mW, and a spectrum of the pump is also measured and shown in Fig. 5 as a reference. After normalizing the amplitudes at the laser wavelength (1017.15 nm) to the same level (see inset near 1017.15 nm), it can be observed that more pump power is
absorbed with increasing fiber length (see inset near 976 nm). However, the spectra beyond the lasing wavelength are nearly identical to each other, indicating that no significant ASE was present in the laser. Therefore, it can be concluded that a test fiber length of 5 m to 8 m is close to optimal for efficient lasing, which agrees with the power measurements as well as the simulation results discussed below.

At each test fiber length, the output power versus pump power is also recorded via a power meter. Since both pump and laser light are present at the output end, the exact output power should be the measured output power multiplied by a correction factor $\xi$ defined to be

$$\xi = \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda) d\lambda}{\int_0^{\infty} I(\lambda) d\lambda}$$

where $I(\lambda)$ is the measured spectrum, and $\lambda_1 = 1016.55$ nm and $\lambda_2 = 1017.8$ nm, corresponding to the wavelengths where a 60 dB decrease from the peak (1017.15 nm) occurs (see the two dashed lines in the right-hand inset in Fig. 5). The output power ($P_{\text{out}}$) versus pump power ($P_{\text{pump}}$) for all the investigated cases as summarized in Fig. 6 utilize this correction factor at each data point.

Next, a theoretical laser model based on the rate equations [48] is constructed. First, an inhouse solver with a 20-layer approximation of the core was used to simulate the fundamental mode of the test fiber at 1017.15 nm ($E_1$). The result is shown in Fig. 7(a), with the peak normalized to 1 for convenience. From the result, the mode effective area and overlap integral with the active ions in the core can be calculated to be 7.616 $\mu$m$^2$ and 98.06%, respectively, which will be used in the laser model. Meanwhile, the mode of the passive fiber in the system (Nufern 1060-XP) at 1017.15 nm ($E_2$) is also calculated and normalized in a way that $\int \int_{-\infty}^{\infty} |E_1|^2 r dr d\phi = \int \int_{-\infty}^{\infty} |E_2|^2 r dr d\phi$. The result is shown in Fig. 7(b), having the same scale bar as Fig. 7(a). It is obvious that $E_2$ is wider and shallower than $E_1$ as a result of a larger core and smaller index difference. An overlap integral between $E_1$ and $E_2$ is then calculated and indicates a 1.45 dB splice loss between the two fibers, which is very close to the measured value of 1.49 dB. Then, by plugging in these parameters as well as those characterized in Section 3A, the output power vs pump power for different active fiber lengths is simulated and plotted as the “Theoretical Model” in Fig. 6.

To determine the QCE of the fiber, linear fits are applied to the experimental power data, from which the experimental slope efficiencies ($\eta_e$) can be determined. Next, the modeled slope efficiencies ($\eta_m$) are extracted from the simulation results and summarized in Table II along with the $\eta_e$ values. It can be observed that $\eta_e$ is smaller than $\eta_m$ in all the cases. The reason, like that in Section 3B, is the assumption of a 100% QCE in the fiber. In other words, the model assumes that for each pump photon that was absorbed by the test fiber, a corresponding signal photon was generated. However, the fact that nonradiative processes also take place in the fiber violates this assumption and decreases the slope efficiencies. To be more specific, only
the QCE of the absorbed pump power contributes to the laser output power, while the proportion (1-QCE) of the pump power ends up as heat. As such, at each data point the measured output power should be QCE multiplied by the modeled output power. Therefore, the value of $\eta_e/\eta_m$ represents nothing more than the QCE of the fiber, which ranges from 98.58% to 99.13% in the four cases. In comparison, the calculated QCE from the Brillouin setup (Section 3B) is around 99.07%, which lies in the range determined by the linear laser. Therefore, it can be concluded that the two methods substantiate the accuracy of the fiber QCE value. However, the QCEs determined from the linear laser have a greater intrinsic uncertainty than that determined from the Brillouin apparatus. The reason is that the Brillouin setup is much more sensitive to variations in the QCE. For example, if the QCE of the fiber changes from 99% to 99.1%, the measured slope efficiency in the linear laser will also increase by $\sim$0.1%, which can be hard to distinguish. On the other hand, for the same change in the QCE in the Brillouin setup, using Eqn. (10) the $\Delta T_c/\Delta T_m$ value will increase by $\sim$2.3%, or $\sim$23 times greater than the change in the linear laser.

Finally, it is necessary to discuss the origin of possible errors intrinsic to the proposed method. A first source of error is the temperature calibration of the Brillouin scattering signal. For instance, the temperature of the water bath may vary while acquiring the Brillouin spectra, adding uncertainty to the measurement of the peak frequency. Second, the theoretical model depends on an accurate characterization of the average emission wavelength, which further relies on a clear emission spectrum. However, for fibers with low active dopant concentration (such as the test fiber here), the emission from the fiber is weak and the measured spectrum can be very noisy, introducing errors in the average emission wavelength. These errors decrease as the dopant concentration increases. Third, fibers designed for high-power applications may have an intrinsically low Brillouin scattering strength [49]–[52], rendering weak and potentially noisy spectra. Last but not least, the thermal conductivity of the core ($k_1$) is assumed to be that of silica in the model. However, this value can differ when dopants are incorporated in silica, thereby adding errors to the modeling result. Therefore, in order to minimize the aforementioned errors, a highly temperature-stable water bath or other temperature-controlled environment should be used during the calibration, sufficient averaging should be applied when measuring the emission and Brillouin spectra, and these have all been given careful attention in this work. As for $k_1$, it is found that for the test fiber used in this paper, the temperature of the core center will only decrease 0.1 mK even if $k_1$ is doubled. Therefore, $k_1$ can be approximated to be the value of silica without adding significant errors.

### IV. Conclusion

In conclusion, proposed here is a method, based on Brillouin scattering, for the characterization of the quantum conversion efficiencies in Yb-doped fibers. An adapted version of the heterodyne approach was designed, which measures the fiber temperature change through the frequency shift in Brillouin scattering spectra when the fiber is pumped by a laser source. With the usage of aerogel tiles inside of a vacuum chamber, conductive and convective thermal transport are minimized so that a precise temperature of the fiber can be measured. The setup is all-fiber and operates over a wide range of fiber temperatures. A theoretical model based on the thermal conduction equations was constructed, which then was compared to the experimental results, and from which the QCE of the fiber was determined. To prove the method, a commercial Yb-doped fiber was investigated, and the measurement indicates a 99.07% QCE. Finally, a linear laser experiment was performed to confirm this QCE value and the results were in excellent agreement with the QCE value from the Brillouin setup. Origins of the errors associated with the measurement were discussed, with corresponding solutions to minimizing each of them having been provided. This simple and sensitive platform is expected to be useful in researches toward the optimization of fiber designs in high-power lasers. It can also be used as a sensitive temperature sensor in the study of ASF cooling in fibers.

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