Thermal Characteristics Of Brillouin Microsphere Lasers

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Abstract—In this paper, we investigate thermal characteristics of Brillouin microsphere lasers theoretically and experimentally. A theoretical model for Brillouin lasing in microcavities is constructed based on couple mode theory. The analytic correlation between Brillouin lasing and thermal power is given. To track the thermal response of Brillouin microlasers, we introduce two kinds of thermal perturbations by either tuning the wavelength of pump wave or varying the surrounding temperature. It is shown that the output power of Brillouin lasers is sensitive to and linearly varied with the thermal change of the mode area and surroundings. The optical bistabilities induced by the resonant transition of the pump wave or Brillouin lasing is further studied and the thermal behavior is well explained by the thermal dynamics of whispering gallery modes. Our results demonstrate that Brillouin microlasers with stable performances hold great potential for sensor applications since thermal or object-induced perturbations on lasing can be simply tracked by the variation of output power.

Index Terms—Thermal characteristics, microsphere, Brillouin microlaser.

I. INTRODUCTION

B rillouin lasing or stimulated Brillouin scattering (SBS) is an coherent nonlinear phenomenon originated from the inelastic scattering of material lattice, where a pump signal wave and the scattered Stokes wave interferes with each other and the mechanical oscillation induced by the electrostriction effect is formed as an acoustic wave at certain frequency[1]-[4]. In the past decades, the SBS has attracted intensive interests for its unique features, such as low threshold and narrow linewidth[4], and been widely developed and investigated in fiber-based system[3], in on-chip photonic circuits[5]-[7] and in whispering gallery mode(WGM) microcavities[8]-[11]. WGM microcavities with high-Q resonances can greatly enhance the light-matter interaction and have become a promising platform for the achievement of low threshold SBS[8]-[18]. Up to date, a variety of cavities have already been employed for SBS, such as silica/tellurite microspheres[10]-[14], silica rods/microbottles/bubbles [15]-[17], and silica/fluoride microdisks[9][18]-[20]. The SBS can be effectively excited when both pump and scattered Stokes waves are involved into cavity resonances. In addition, some SBS applications, such as microwave synthesizers and filters[21][22], slow light for light storage[23][24], and gyroscopes[25], have been recently reported. Among all the above mentioned cavities, silica sphere cavities with dimensions of hundreds micrometers possess unique features of ultra-rich mode resonances and easy fabrication[26], which enables the thermal latching of pump wave to WGM resonances fairly easily and is particularly suited for the SBS realization without repeated sweeping of pump wave.

In this work, thermal characteristics of Brillouin silica microsphere lasers are investigated theoretically and experimentally. In section II, we construct a theoretical model for Brillouin lasing in microcavities based on couple mode theory and obtain an analytic correlation between Brillouin lasing and thermal power. In section III, two kinds of thermal perturbations are proposed by either tuning the pump wave or varying the surrounding temperature for the study of thermal responses of Brillouin lasing. In section IV, we perform the experimental investigation by employing the mechanically packaged silica sphere resonator and verify that the lasing output is sensitive to and linearly varied with the resonant shift that is induced by the thermal perturbation. Some lasing behaviors, such as optical bistabilities due to the resonance transition of pump wave or Brillouin lasing, and up to 41.7dB...
of side mode suppression ratio (SMSR) are presented. Finally, the conclusions are given in Section V.

II. THEORETICAL MODEL OF BRILLOUIN LASING

Fig. 1(a) shows a schematic plot of Brillouin microsphere lasers. In the theoretical model, we set $s_{in}(t)$ and $s_{b}(t)$ as amplitudes of incident and transmitted waves in the taper while $P_{in} = |s_{in}|^2$ and $P_{b} = |s_{b}|^2$ represent the incident and transmitted pump power. The power wave coupled into cavity $P_{c}$ is equivalent to $P_{in} - P_{c}$. $b_{b}(t)$ and $b_{j}(t)$ are set as energy amplitudes of the pump wave (regarded as the 0th-order Brillouin lasing) and the $j$th-order Brillouin lasing as $W_{0} = |b_{b}(t)|^2$ and $W_{j} = |b_{j}(t)|^2$ represent their energies stored in the microsphere. Based on coupled mode theory[27], similar to a theoretical model for Raman lasing[28], we can construct the following equations to describe the time evolution of $b_{j}(t)$

\[
\frac{\partial b_{0}}{\partial t} = (i\Delta\omega_{0} - \kappa_{0} - g_{s}^{2}W_{1})b_{0} + \sqrt{2\kappa_{0}}s_{in}
\]

\[
\frac{\partial b_{j}}{\partial t} = (-\kappa_{j} - g_{s}^{j}W_{j+1} + g_{s}^{j}W_{j-1})b_{j} + \sqrt{2\kappa_{j}}s_{in}
\]

\[
\frac{\partial b_{N}}{\partial t} = (-\kappa_{N} + g_{s}^{N}W_{N+1})b_{N}
\]

(1)

where $\Delta\omega_{0}$ is the detuned angular frequency between pump wave and cavity resonance, $\kappa_{j}=\kappa_{j}^{+}/\kappa_{j}^{-}$ is the total field loss rate which comprises of the intrinsic loss rate $\kappa_{j}^{+}$ and the loss rate $\kappa_{j}^{+}$ associated with waveguide coupling. $g_{s}^{j} = \Gamma g_{0}c^{2}/(2n^{2}V_{mf})$ is defined as intra-cavity Brillouin gain coefficient, where $g_{0}$ is Brillouin gain in bulk silica, $n$ is refractive index, $c$ is the light velocity in vacuum, $V_{mf}$ is mode volume of the $j$th-order Brillouin lasing coupled WGM, $\Gamma$ stands for the mode overlap.

For steady state at which the powers or energies of both pump wave and Brillouin lasing in microsphere are invariable, the pump power $P_{c}$ is dissipated into intrinsic loss and the $j$th-order Brillouin lasing power as other power loss routes or nonlinear phenomena are ignored when single or cascaded Brillouin lasing dominates in microsphere:

\[P_{c} = 2(\kappa_{0}^{+} + g_{s}^{1}W_{1})W_{0}.
\]

Additionally, $P_{c}$ can also be derived from the total power $P_{in}$ used for pumping, namely, the power inserted into taper:

\[P_{c} = \frac{4\kappa_{0}^{+}(\kappa_{0}^{+} + g_{s}^{1}W_{1})}{(\kappa_{0}^{+} + g_{s}^{1}W_{1})^{2} + \Delta\omega_{0}^{2}}P_{in}.
\]

(3)

The power of the $j$th-order Brillouin lasing $P_{j} = P_{j}^{+} + P_{j}^{-}$ includes the intrinsic loss $P_{j}^{+} = 2\kappa_{j}^{+}W_{j}$, the power $P_{j}^{-} = 2\kappa_{j}^{-}W_{j}$ coupled out by waveguide and the power $P_{j}^{+} = 2g_{j}^{s}W_{j+1}W_{j}$ as the pump wave for the next order Brillouin lasing. At the same time, $P_{j}^{+}$ originates from $P_{j+1}^{-}$ and $P_{j}^{-} = 2g_{j}^{s}W_{j}W_{j+1}$. Thus we can obtain the relation between $W_{j+1}$ and $W_{j}$:

\[W_{j+1} = \frac{g_{j}^{s}W_{j+1} + \kappa_{j}^{-}}{g_{j}^{s}}.
\]

(4)

For the last order ($N^{th}$) lasing, $W_{N+1} = 0$, $W_{N+1} = \kappa_{N}^{+}/g_{s}^{N}$ can be directly obtained and then $W_{j+1} = 1$ can be derived from $W_{N}$ as $m = 1, 2, 3, ...$ from Eq.(4). If $N-1-2m=1$, we can obtain $W_{1}$ from Eq. (2) and Eq.(3), or we can obtain $W_{1}$ when $N-1-2m=0$.

Based on the obtained $W_{0}$ or $W_{1}$, the energies $W_{j}$ of the other orders Brillouin lasing can be derived from Eq. (4) as well. Finally, the corresponding Brillouin lasing output and intrinsic loss can be obtained:

\[P_{j}^{+} = 2\kappa_{j}^{+}W_{j},
\]

and

\[P_{j}^{-} = 2\kappa_{j}^{-}W_{j},
\]

respectively. Fig. 1(b) shows an example of output power for a 5-order cascaded Brillouin lasing, whereas $P_{in}=20mW$, $\kappa_{j}^{+} = 0.8\pi \times 10^{6}Hz$, $\kappa_{j}^{-} = 4k_{j}^{s}$, $g_{0}^{s} = 1.75 \times 10^{4}Hz^{2}/mW$, and $\Delta\omega_{0} = k_{j}^{s}$. One thing should be noted is that the odd and even orders Brillouin lasing propagate in the backward and forward directions, respectively, and here backward Rayleigh scatterings are ignored.

Finally, we can obtain the total intrinsic loss power:

\[P_{l} = \sum_{j=0}^{N} P_{j}^{+},
\]

including both the intrinsic losses of all orders Brillouin lasing and pump wave. We know that most of optical losses induced by the material absorption are transferred into heat, thus $P_{l}$ can be approximately considered as heat power $P_{h}$ in microsphere.

For single Brillouin lasing($N=1$), the Brillouin lasing output $P_{l}$ and thermal power $P_{h}$ can be derived as:

\[P_{l}^{+} = 2\kappa_{1}^{+}\sqrt{\frac{2\kappa_{0}^{+}P_{in}^{2} + (\Delta\omega_{0})^{2} - 2\kappa_{1}^{+}g_{0}^{s}}{g_{1}^{s}}},
\]

and:

\[P_{h} = 2\kappa_{1}^{+}\sqrt{\frac{2\kappa_{0}^{+}P_{in}^{2} + (\Delta\omega_{0})^{2} - 2(2\kappa_{1}^{+} - \kappa_{1}^{s})g_{1}^{s}}{g_{1}^{s}}},
\]

As the pump wave is completely coupled with resonances, namely $\Delta\omega_{0} = 0$, $P_{l}^{+}$ and $P_{h}$ reach the maximum values $P_{l}^{+\_m}$ and $P_{h\_m}$, the minimum threshold of single Brillouin lasing can also obtained:

\[P_{in} = \frac{\kappa_{0}^{+}\kappa_{1}^{+}}{2\kappa_{0}^{+}\kappa_{1}^{s}}
\]

(10)

when the Brillouin lasing output equals to 0. For the cascaded Brillouin lasing, if the last order $N^{th}$ is odd/even number, the odd/even number order Brillouin lasing is relative to $\Delta\omega_{0}$ as that of even/odd number order lasing is only relative to $\kappa_{j}^{+}$, $\kappa_{j}^{s}$ and $g_{j}^{s}$. In the following, only single Brillouin lasing is considered.

III. THERMAL PERTURBATIONS

Two kinds of thermal perturbations on Brillouin lasing are proposed. One is to tune the wavelength of pump wave and the other is to vary the surrounding temperature. When the pump wavelength is manually tuned by a certain value, the resonance will follow the shift of the pump wave as optical resonances are thermally latched by pump wave. The relation between the variation of thermal power $\Delta P_{h}$ and the tuning of pump wavelength $\Delta\lambda$ can be briefly expressed as $\Delta P_{h} = K\Delta\lambda/\zeta$.
where $K$ is the thermal conductivity between the mode area and the surroundings with unit of W/K, $C_p=13.89$ pm/K is the thermal coefficient of the wavelength drift of silica, taking into account both the influences from the thermal-induced refractive-index change and cavity expanding[29]. For the single Brillouin lasing, as shown by Eq. (8) and Eq. (9), the relation between the change and cavity expanding [29]. For the single Brillouin lasing output $\Delta P_b$ and the tuning of pump wave $\Delta \lambda_p$ can thus be constructed as

$$\Delta P_b = \frac{\kappa_1}{\kappa_1'} K \Delta \lambda_p \quad \text{(11)}$$

the coupling frequency $\kappa_1'$ is usually larger than the intrinsic loss $\kappa_1$ for the adhesive coupling of taper, because the coupling loss led by coupling waveguide (without power coupled into cavity) is usually higher than the intrinsic loss of the cavity, which explains why most of Brillouin lasing power can be collected and up to 90% of total power efficiency can be realized[9].

As the pump wavelength $\lambda_p$ is manually tuned by $\Delta \lambda_p$ whose minimum value is determined by the tuning resolution of pump laser, the total variation of Brillouin lasing output $\Delta P_b$ can be obtained from Eq. (11). Fig.2(a) shows the variation of $\Delta P_b$ as $\Delta \lambda_p$ is swept by 3pm with a velocity $v_p=\pm1$nm/s, which is calculated based on the thermal dynamic equations of microsphere[30]. $\Delta P_b$ first jumps by a height of $h$ in a short time of $\Delta t$ from a thermally steady state to an un-steady state, then linearly increases/decreases following the sweeping of $\lambda_p$, and eventually increases/decreases to the secondary steady state with a power jump of $h$ as well. The inset shows the expanded evolution of $\Delta P_b$ as $\lambda_p$ starts sweeping. The jump $h$ is led by the temperature lag of thermal response from the pump wave sweeping due to the fact that the temperature can’t jump abruptly, where $h$ is proportional to the sweeping speed $v_p$, while $\Delta t$ is proportional to input power $P_b$. The over quick sweeping of $\lambda_p$ generally leads to a great lag of thermal response, if this lag is great enough as the power coupled into cavity is less than the initial value, the resonance $\lambda_p$ does not shift in red direction, but shift in blue direction and the thermal latching breaks. On the contrary, if the pump is swept in blue direction, the maximum value of jump power $h$ is equivalent to the initial Brillouin lasing output.

As the surrounding temperature $T_s$ is increased/decreased by $\Delta T_s$, the thermal power $P_h$ will decreases/increases by a value of $K \Delta T_s$, and accordingly the variation of Brillouin lasing output $\Delta P_b$ can be derived from Eq.(11):

$$\Delta P_b = -\frac{\kappa_1'}{\kappa_1} K \Delta T_s. \quad \text{(12)}$$

We assume $T_s=T_0+v_h t$ increases linearly, and $\Delta T_s=T_0+\Delta T_s e^{\frac{-t}{\tau}}$ decreases exponentially, where $T_0$ is the initial temperature, $v_h$ is the temperature increasing speed, and $\tau$ is the thermal relax time. In order to mimic the variation in $\Delta P_b$, we set $v_h=0.1K/s$, $\tau=50$s and the temperature increasing time is 100s, other parameters are the same as those used in Fig.2(a). The results are shown in Fig. 2(b), the lasing output $P_b$ decreases by -1.9mW from the initial value in 100$s$ and then recovers to the initial value as the heater cools down for 300$s$. $P_b$ follows the change of surrounding temperature $T_s$ and shows no jump. On the other hand, if $P_b$ is tracked by a power meter or oscilloscope, the thermal detection of the surrounding temperature can be realized.

![Fig. 2. (a) The variation of the Brillouin microlaser output power $\Delta P_b$ as $\lambda_p$ is swept by 3pm with a speed of $v_p=\pm1$nm/s. The inset is the expanded demonstration of dashed rectangle with the same time scale, where the power coupled into taper $P_c=50$mW, $k_0/k_1=0.2$, $\gamma=1.75\times10^4$Hz/mW, the thermal capacity of mode area $c_p=2.363\times10^4$ mJ/K, $K=4.73\times10^5$ mW/K and $\kappa_1=\kappa_0=2\pi\times10^4$Hz, the initial value of $\Delta \lambda_p=\kappa_0$. (b) $\Delta P_b$ depending on time for both heating and heat dissipation processes.](image)

![Fig. 3. Schematic illustration of measurement system of Brillouin microsphere laser.](image)

### IV. EXPERIMENTAL DEMONSTRATIONS OF THERMAL PERTURBATIONS ON BRILLOUIN MICROSPHERE LASER

#### A. Package of microspheres for stable performances of Brillouin lasing

Fig. 3 shows a schematic illustration of the experiment setup for the measurement of microsphere Brillouin lasers. A tunable external cavity laser (TECL) produced by Photonetics Incorporation with the type of Tunics-plus at $C$ band and a typical linewidth of $150kHz$ is employed as the pump source, the wavelength resolution of TECL is $1pm$, and the typical wavelength and power stability are $\pm3pm/h$ and $\pm0.01dB/h$. 


Before the experimental study of thermal characteristics of Brillouin microlasers, a mechanical module is designed and used to package the sphere cavity with a fiber taper in order to stabilize the coupling and achieve stable performances of the Brillouin laser. Detailed packaging steps are presented in Fig. 4. A fabricated cavity is firmly fixed by a bolt on a mechanical module; (b) The position of the module with the resonator is tuned by a 3D translation stage to approach to the pulled taper under the monitoring of a microscope. The wide cross section of the sphere cavity allows remarkable coupling tolerance near the equator. (c) The sliders on the module are jacked up to abut against the taper; (d) A photodetector, and the real-time variation of power can be monitored by an oscilloscope.

![Packaging steps of the sphere cavity with a fiber taper. (a) A fabricated cavity is firmly fixed by a bolt on a mechanical module; (b) The position of the module with the resonator is tuned by a 3D translation stage to approach to the pulled taper under the monitoring of a microscope. The wide cross section of the sphere cavity allows remarkable coupling tolerance near the equator. (c) The sliders on the module are jacked up to abut against the taper; (d) Ultraviolet(UV) glue is dripped on the top of sliders to fix the taper after several minute solidification. (e) A packaged sphere-taper with two connecting ports. (f) The side view of a sphere cavity coupled with a taper.](image)

respectively. To perform thermal perturbations on the Brillouin laser, sphere cavities fabricated from a 3 millimeter-diameter quartz rod by a mechanical method are employed[31], and a heater, positioned in the box, is used for tuning the temperature of environment. A fiber taper with diameter ranging from 2µm to 4µm, pulled from a single mode fiber, is used to couple the pump wave into the cavity. The power of the backward scattered Brillouin lasing is coupled out by the same taper, then collected by an optical circulator, and subsequently divided into several routes for microlaser diagnosis, for example, using an optical spectrum analyzer (OSA) and a power meter for measuring optical spectra and power. In order to track the real-time variation of the laser output, one of routes is coupled into a photodetector, and the real-time variation of power can be monitored by an oscilloscope.

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The transmission spectrum of the packaged sample is measured and shows typical resonances with Q factors higher than 1×10^8 which are not spoiled due to the packaging. In order to couple the pump wave into cavity, the wavelength of the TECL is manually tuned to latch the pump wave to one of the WGM resonances and the detuning frequency from the coupled resonance Δω0 is passively chosen. If there exists one resonance located in the Brillouin gain curve, the spontaneous Brillouin scattering will be amplified and transformed into SBS due to longer photon life or higher intensity induced by WGM resonances. The detuning Γ between WGM resonance and Brillouin gain curve is also passively chosen and takes effects on intracavity Brillouin gain g'. In order to present the stability of Brillouin microsphere laser, three optical spectra of a 5-order cascaded Brillouin lasing with a time interval of 10 minutes are measured and shown in Fig. 5. The highest peak is the 1st-order red-shifted Brillouin lasing while only the backward scattered light is collected. The 1st, 3rd and 5th peaks are the reflected pump wave, the 2nd, and the 4th-order Brillouin lasing, which are resulted from intra-cavity Rayleigh scattering[32][33]. The real time output power is tracked by an oscilloscope as presented in the upper part, the slight decrease of output power is led by the decrease of pump power(amplifier). The inset shows the expanded peak of the 1st-order of Brillouin lasing with a power fluctuation less than 0.2dBm. The results indicate that the coupling strength between the taper and sphere is stable and the mechanical packaging enables stable performances of Brillouin lasing (we also performed measurements on un-packaged spheres in free air, the output is confirmed to be unstable). It means that the coupling noise induced by the displacement of taper and cavity is effectively under control.

B. Wavelength tuning of Pump wave

To experimentally investigate thermal behaviors of the Brillouin microsphere laser, the pump wavelength λp is firstly swept by steps of 10pm over the optical resonances until lasing is realized. The tuning step is then minimized to 1pm. Fig. 6(a) shows a typical variation of lasing output P as λp is tuned from point ‘a’ to ‘b’ and then to ‘c’ and finally jump to ‘d’ in a cavity of 620µm. The pump power Pp, coupled into the taper is ~100mW. The total tuning of ~150pm can be divided into 7 segments denoted by the number from 1 to 7. Fig. 6(b) schematically shows the relative positions of pump λp and coupled resonance λc of four states denoted by points ‘a’, ‘b’, ‘c’ and ‘d’. ‘c’ and ‘d’ indicate the nearly complete and incomplete latching states of the pump wave, respectively, while ‘a’ and ‘b’ fall in between them. As predicted by Eq.(11), ΔPp varies linearly with Δλc in all segments from 1 to 7 upon a coefficient κ/κ1, even though slight noise exists as Rayleigh scattering power is not transferred into thermal power. The power transitions between adjacent segments are led by the resonance transitions of pump wave or Brillouin lasing. The pump is tuned in red direction from point ‘b’, more
power is coupled into cavity and all the WGM resonances (including pump coupled resonance) drift synchronously due to thermal effects (segment 5). If the pump power coupled into cavity $P_p$ increases to the maximum value for the coupled resonance, namely $\lambda_r - \lambda_0 = 0$ or $\Delta \omega \approx 0$, the thermal power $P_t$ can’t support the resonance shift as the pump $\lambda_p$ is further tuned (transition between 5 and 6), and the thermal latching breaks. The pump power $P_t$ coupled into cavity decreases to zero and the resonances start to shift in blue direction during the process of heat dissipation until another resonance latches again. The newly coupled resonance should have greater coupling frequency $\kappa'$ (see from Eq.(9)), otherwise thermal power still cannot support the already induced resonance shift (assume a slight blue shift occurs as the latching transits from one resonance to another). The above mentioned process repeats for the newly coupled pump wave (segment 6), and if there is no resonance to get a higher $\kappa'$, the latching completely breaks and finally $P_t$ decreases to 0 (point ‘d’). On the contrary, if the pump $\lambda_p$ is tuned in blue direction (segment 1), the thermal power $P_t$ decreases and the resonances $\lambda_r$ drift to the shorter wavelength. The output transitions between segments 1 and 2 or others cannot be attributed to the resonance transitions of pump wave, it is because only when $P_t$ decreases to zero, the transition can happen as the pump $\lambda_p$ is further tuned. Thus, we attribute the hopping of the output to the lasing transition between different resonances as $\lambda_p$ is tuned in blue direction, because the band width of the Brillouin gain spectrum is a few tens of megahertz which may cover several resonances of large sphere cavities (this can be confirmed by the measured transmission spectrum), and the lasing competition between resonances may exist due to the dispersion of resonance shift. In Fig. 6(c), the Brillouin lasing spectrum at point ‘c’ is presented.

The optical bistabilities due to the resonance transition of pump wave or Brillouin lasing are quite universally observed in large cavities with intense resonances. Obviously, the detuning wavelength $\lambda_d$ (between resonance and pump wave) is different at ‘C’ and ‘A’ states. If the pump coupled resonances are the same one at ‘C’ and ‘A’, the resonance wavelength $\lambda_r$ should be the same as $\lambda_d$ is latched by the same $\lambda_p$, the thermal power $P_t$ should be the same as well. However, as shown by Eq.(8) and Eq.(9), $P_t$ should be different as the lasing output $P_l$ is different, it is inconsistent with the assumption of the same coupled resonance of pump wave. Thus the resonances transition of pump wave certainly exists and optical bistabilities are attributed to the resonance transitions of pump wave and Brillouin lasing with different $\kappa'_{1}$, $\kappa'_{2}$ and $\gamma'_{2}$.

In the following, we give five typical results from four samples with diameters ranged from ~200μm to ~600μm, including two results from a ~300μm-diameter cavity. As shown in Fig. 7(a), where we estimate the total tuning bandwidth $A_w$ by extrapolating the lasing output $P_l$ to zero, since we cannot fully tune the pump $\lambda_p$ as $\lambda_r$ is randomly latched to one of WGMs. $A_w$ is 104pm and 102pm for the 300μm-diameter cavity, and 38pm, 510pm and 400pm for cavities with diameters of ~620μm, ~195μm and ~220μm, respectively. Smaller cavities usually accommodate greater $A_w$, due to the smaller heat conductivity $K$. For the same cavity, $A_w$ varies from mode to mode, the thermal power $P_t$ or Brillouin lasing output $P_l$ is accordingly different. In addition, different $P_l$ also leads to different $P_r$ and $A_w$. Fig. 7(b) shows a real-time $P_t$ tracked by an oscilloscope for back and forth tuning in a 300 μm-diameter sphere. The pump wavelength $\lambda_p$ is first tuned from $\lambda_0$ to $\lambda_1$ in the blue direction, and then tuned back to $\lambda_0$. Here, the tuning interval keeps 10pm except that $\lambda_3$-$\lambda_4$ = 25pm. The lasing outputs are estimated to be 2.50, 2.17, 1.75, 1.38, 1.70, 2.51 and 2.90mW respectively. The temperature sensitivity of the mode region is thus between 0.444mW/K and 0.584mW/K. Generally speaking, Brillouin lasing in larger cavities has greater sensitivities than that of smaller cavities for the same thermal power $P_t$, while it is mainly determined by the total lasing power conversion efficiency. For example, $P_t$ is usually lower and $A_w$ is smaller for a great lasing output. As shown in Fig. 7(c), we give a spectrum from a ~300μm-diameter Brillouin laser, where the lasing output is ~26.2mW and the total power conversion efficiency is estimated to be 67%~87%. Therefore, the thermal sensitivity is greater than 3.64mW/K (0.262mW/pm) as total tuning bandwidth $A_w$ is less than 100pm for a smaller thermal power $P_t$. The demonstrated 41.7dB of SMSR, to the best of our knowledge, is the highest reported value to date in WGM Brillouin microlasers.
C. Temperature variations of surroundings

The thermal influence on Brillouin microcavities induced by temperature variations of surroundings is also studied. Firstly, the system is heated up to a certain temperature $T_i + \Delta T$ ($T_i$ is the room temperature). When heating stops, the lasing output is recorded within a few minutes as the thermal power is dissipated from the heater into air and the temperature of the cavity decreases accordingly. Finally, the heater is operated again with different heating-up speeds and time. As shown in Fig. 8, the measured results are fitted by setting proper parameters. The thermal sensitivity of Brillouin lasing on the surrounding temperature is estimated to be within the range from 0.51 mW/K to 0.55 mW/K, close to the values of that in mode area. The results indicate that the Brillouin lasing output can be linearly tuned by increasing or decreasing the temperature of surroundings, which hold great potential for the application of thermal sensing.

Fig. 8. Brillouin lasing output versus thermal tuning time. Both heat dissipation and heating processes are considered.

V. CONCLUSION

In conclusion, the thermal characteristics of Brillouin silica microcavities have been investigated. The constructed analytic model based on couple mode theory predicts that the output power of Brillouin lasing will linearly vary with the resonant shift induced by the thermal perturbations. In order to verify the theoretical prediction, mechanically packaged microparticles are employed and experiments are simply performed by either tuning the wavelength of pump wave or varying the environmental temperatures. The results clearly confirm our theoretical prediction. Optical bistabilities induced by the resonant transition of pump wave or Brillouin lasing, are demonstrated and well explained by thermal dynamics of microcavities. On the other hand, by simply tracking the output power of Brillouin laser, we can detect the temperature change of environments resulting in the shift of microsphere resonances, which demonstrates the potential application of Brillouin microcavities lasers for thermal sensors. Except thermal perturbations, optical perturbations on evanescent wave, such as adherence of biomolecules and optical coupling from a probe light, can also be detected from the variation of Brillouin lasing output power.

REFERENCES


