Recent progress in x_3-related optical process experimental technique. Raman lasing.

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Abstract: We describe theoretically and verify experimentally a simple technique for analyzing conversion efficiency and threshold of all-resonant intracavity Raman lasers. The method is based on a dependence of the ring-down time of the pump cavity mode on the energy, accumulated in the cavity.

Transient processes in lasers are important from both fundamental and practical points of view. For instance, they provide information about properties of the gain material [1] as well as of the decay of an unstable state [2]. We focus on dynamics of continuous wave (CW) solid state Raman lasers [3, 4] in this work. The lasers recently attracted a lot of attention because of their possible chip-scale integration and wide tunability [5, 6]. Transient regime of CW Raman lasers, especially their switching-on dynamics, was studied in [7, 8]. We here study switching-off dynamics of an all-resonant CW Raman laser and show that the ring-down dependence can be used to find the basic laser parameters such as threshold pump power, Raman gain, conversion efficiency, and quality factors of the pump and Stokes cavity modes. An advantage of the technique is in its ability to characterize the laser behavior without changing power or tuning frequency of the pumping laser. There is no need to lock the resonator to the laser mode as well. We experimentally demonstrate the power of the proposed method testing a Raman laser based on a calcium fluoride whispering gallery mode (WGM) resonator.

The efficiency of Raman scattering depends on the optical field circulating in the media. Once pumping emission is chopped off the mode loses the optical power. This leads to the Raman scattering efficiency decay and ringdown time increasing.

The current decay time of the mode optical field carries information on the raman scattering efficiency and the current level of the field marks the power where this efficiency takes place. This way a single ringdown measurement provides experimentalist with experimental dependence of raman scattering efficiency on the optical power.

With regular ringdown technique we scan the laser over the optical mode and shut the power down at the peak with a simple electrical circuit. Decay rate of the voltage-time dependance taken from the output of the optical detector is proportional to the Raman scattering efficiency.

This simple relation happens if detector absorbs carrier frequency only. In real experiment detector partially receives the raman scattering and this partial coupling should be taken into account to evaluate actual scattering efficiency.

There is a variation of ringdown method which eliminates the problem with partial coupling. Instead of shutting the laser carrier down at the peak of the optical mode we just increase the carrier frequency sweep speed. At certain sweep rate the laser carrier hits the cavity resonance frequency, pump the mode and cross its halfwidth until the mode power decays. After the "hit"-like pump output of the cavity can be split to three sorts of optical emission. The carrier of the laser, the decaying optical mode and the raman scattering. The optical mode has constant frequency and varying intensity. The carrier of the laser has constant power and changing frequency. It is important that in experiment frequency of the raman scattering is nanometers away from the laser carrier and the chosen optical mode.

Detector is not fast enough to recognize the terahertz level beating between Raman emission and laser carrier. On the other hand beating between the laser carrier and the mode can be easily monitored because the frequency distance between them is of megahertz level only. The total detected signal is beating with slowly decaying amplitude changing with time and variation of the background emission. It is important that amplitude of the oscillation carries information about the previously pumped mode only regardless of all coupling efficiencies.

To test the experimental method we conducted two experiments with ultra high-Q CaF_2 WGM resonator [11]. CaF_2 has strong Raman line at 322 cm^{-1} offset from the carrier [12, 13, 14]. We fabricated a disc WGM resonator with radius 0.4 cm (8.2 GHz free spectral range) and 40 μm effective thickness. The resultant WGM cross-section area was less than 20 μm in diameter ($\mathcal{A} \simeq 1.3 \times 10^{-5}$ cm^2).

The Q-factor of the resonator was higher than 10^9. The resonator was pumped with 1.32 μm laser light having maximum of 60 mW power and 4 kHz linewidth. We used cleaved fiber coupler for the input light. The coupling efficiency was better than 30%. The coupling efficiency for the output was better than 90% (the light was collected into a short multimode waveguide and sent to a photodiode). The output pump and Stokes light were separated geometrically so only several percents of the Stokes light were detected.

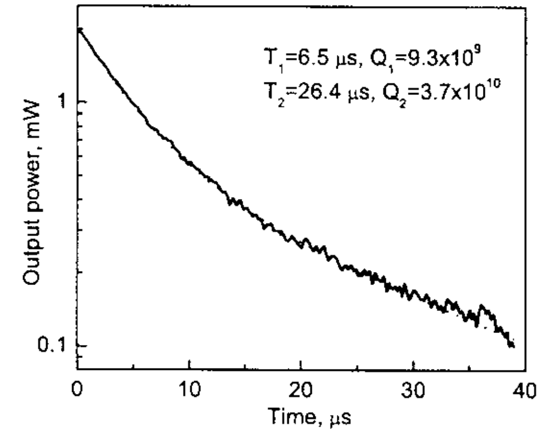

Fig. 1. Typical ringdown characteristic of the fluorite WGM resonator. Solid line corresponds to the experimental observations, dotted line – to the theoretical simulation.

To measure the ringdown of the resonator we used a shutter with 5 ns response time. Characteristic response times of the photodiode and circuits were less than 1 ns. The minimal detected ringdown time exceeded 1 μs, so it was possible to neglect by the characteristic times of the apparatus.

The shape of the light pulse on the exit of the resonator is shown in Fig. 1 by the solid line. The behavior qualitatively corresponds to our expectation. The initial loaded Q-factor of the resonator, 9.3×10^9, increases more than four fold during the decay of the light accumulated in the WGMs, reaching the value of 3.7×10^{10}. Up to our knowledge, this is the maximal Q-factor observed in an open optical dielectric resonator (see, e.g., [11], for details).

We fit the observed dependence using Eq. (??). The theoretical curve is shown by the dotted line in Fig. 1. The fitting parameters are $\sqrt{P_{in}/P_{th}} = 5$, $P_{th} = 1.6$ mW, $2\gamma = (24.6)^{-1}$ s^{-1}, and $\xi = 0.06$, which gives $P_{in} = 40$ mW.

A typical example of such a decay is presented in Fig. 2. Though in this case the quality factor of the WGM was more than an order of magnitude smaller, than in the previous case, we still were able to observe change in the decay rate in time. The Q-factor of the WGM increased more than twice with the observation time. We attributed this increase to the Raman generation in the resonator.

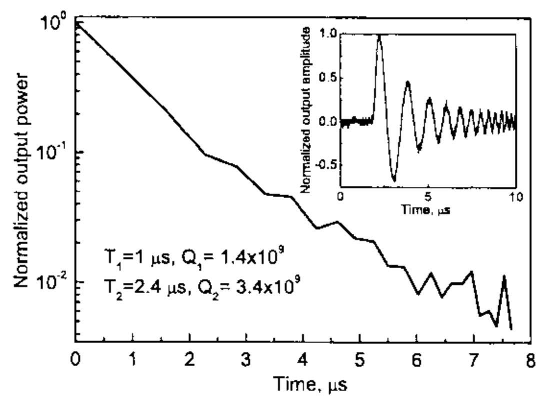

Fig. 2. Decrease of the light power emitted by the resonator mode with time. The curve were taken by finding the beat note (see Inset) maxima and minima. Inset: Typical ringdown characteristic of the fluorite WGM resonator when the frequency of the pump laser is scanned through a selected whispering gallery mode.

In conclusion, we here elucidate transient behavior of an all-resonant ring Raman laser and show that ringdown feature of the device fully characterizes its properties. We present an experimental study of such a Raman laser based on fluorite whispering gallery mode resonator and explain its transient behavior using the proposed theoretical model. Unfortunately we were unable to observe the Stokes light directly because of lack of a spectrum analyzer.
A careful comparison of the abilities of the direct and indirect characterization of the Raman lasers is an issue for the future studies.
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References

1. S. G. Hense and M. Wegener, Phys. Rev. B **55**, 9255 (1997).
2. F. T. Arecchi, V. Degiorgio, and B. Querzola, Phys. Rev. Lett. **19**, 1168 (1967).
3. R. H. Stolen, E. P. Ippen, and A. R. Tynes, Appl. Phys. Lett. **20**, 62 (1972).
4. J. Au Yeung and A. Yariv, J. Opt. Soc. Am. 69, 803 (1979).
5. S. M. Spillane, T. J. Kippenberg, and K. J. Vahala, **415**, 621 (2002).
6. O. Boyraz and B. Jalali, Opt. Express **12**, 5269 (2004).
7. B. Burgoyne, N. Godbout, and S. Lacroix, Opt. Express **12**, 1019 (2004).
8. S. Cierullies, M. Krause, H. Renner, and E. Brinkmeyer, Appl. Phys. B **80**, 177 (2005).
9. R. G. Smith, Appl. Opt. **11**, 2489 (1972).
10. T. J. Kippenberg, S. M. Spillane, B. Min, and K. J. Vahala, IEEE J. Select. Top. Quantum Electron. **10**, 1219 (2004).
11. A. A. Savchenkov, V. S. Ilchenko, A. B. Matsko, and L. Maleki, Phys. Rev. A **70**, 051804 (2004).
12. J. p. Russel, Proc. Phys. Soc. **85**, 194 (1965).
13. A. R. Gee, D. C. O'Shea, and H. Z. Cummins, solid State Commun. **4**, 43 (1965).
14. V. G. Keramidas and W. B. White, J. chem. Phys. **59**, 1561 (1973).