ONLINE SEMINAR ON QUANTUM OPTICS AND RELATED TOPICS

Symmetry breaking of counterpropagating Raman waves in optical microresonators: unexpected findings

Elena Anashkina & Alexey Andrianov

A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), Nizhny Novgorod, Russia

elena.anashkina@gmail.com

Outline

- **Introduction**
- **Symmetric Raman lasing in a silica microsphere:**

  some experimental and theoretical results

- **“Symmetry broken” states of Raman waves:**

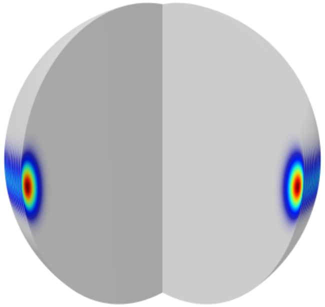
  interesting experimental and theoretical findings

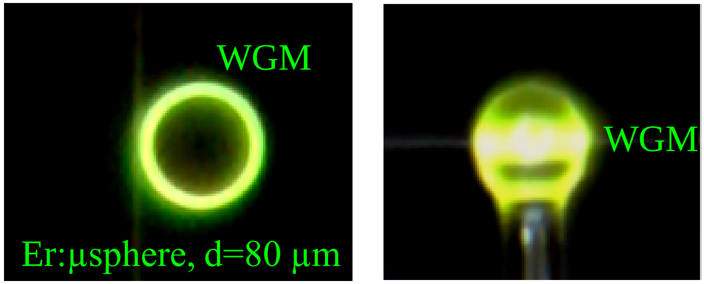
- **Summary**

Introduction

Dielectric microresonators (d~30-500μm) with whispering gallery modes (WGMs):

- Huge Q-factors (10^5-10^{10})
- Small mode volumes
- High power densities
- Very narrow spectral linewidth

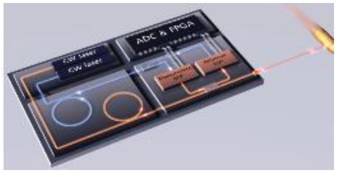




photo, IAP RAS

Many applications

- Optical filtering and switching
- Ultrasensitive sensing
- Frequency stabilization
- Laser linewidth narrowing



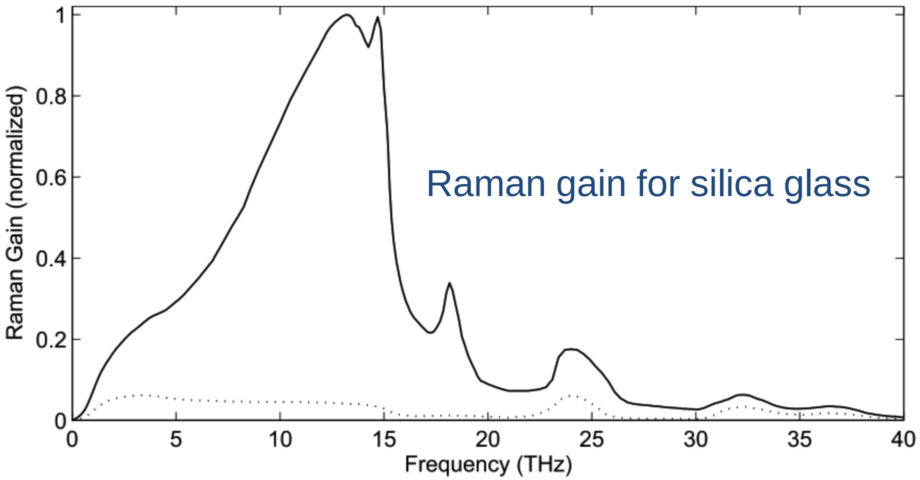
- Precise metrology
- Spectroscopy
- Quantum optics
- Telecommunications

Introduction: nonlinearities in microresonators

- **Kerr nonlinearity**

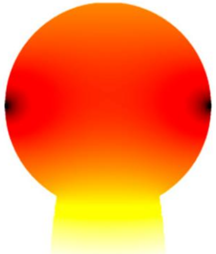
$$n = n_0 + n_2|E|^2$$

- **Raman nonlinearity**



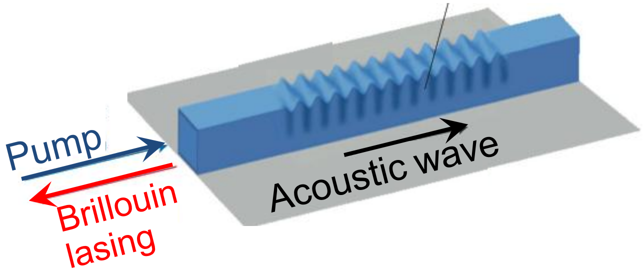
- **Thermo-optical nonlinearity**

$$\Delta n = (dn/dT)\,\Delta T$$



- **Acousto-optical nonlinearity**

(including stimulated Brillouin scattering)

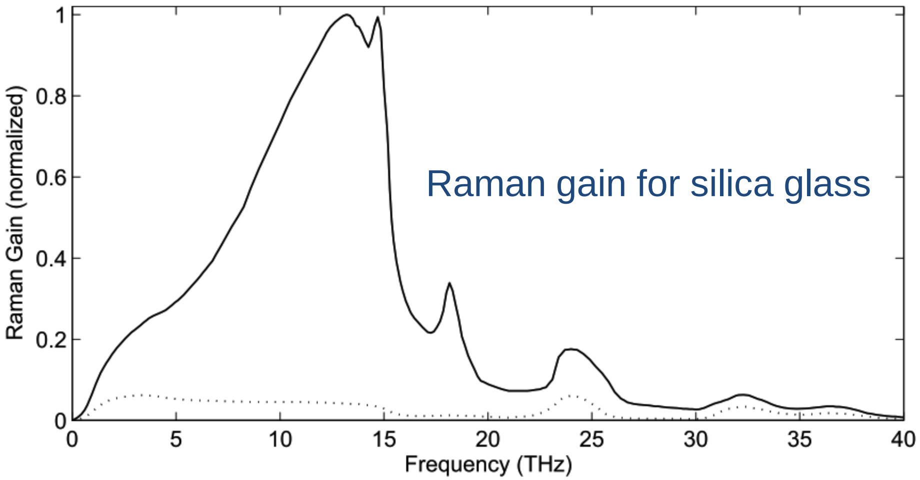


Introduction: nonlinearities in microresonators

- **Kerr nonlinearity**

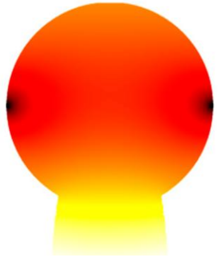
$$n = n_0 + n_2|E|^2$$

- **Raman nonlinearity**



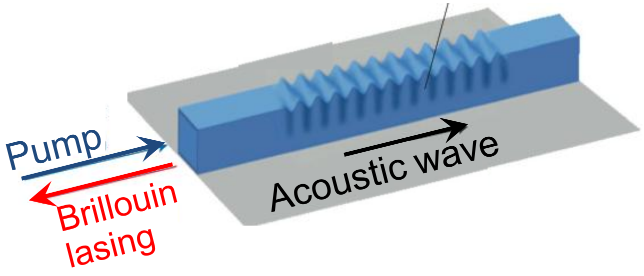
- **Thermo-optical nonlinearity**

$$\Delta n = (dn/dT)\,\Delta T$$

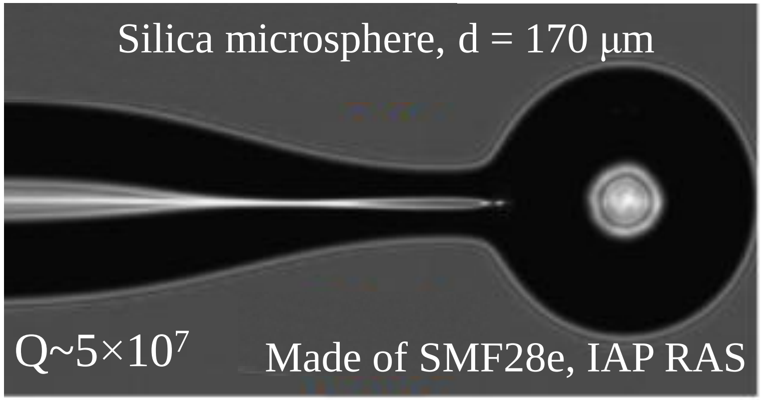


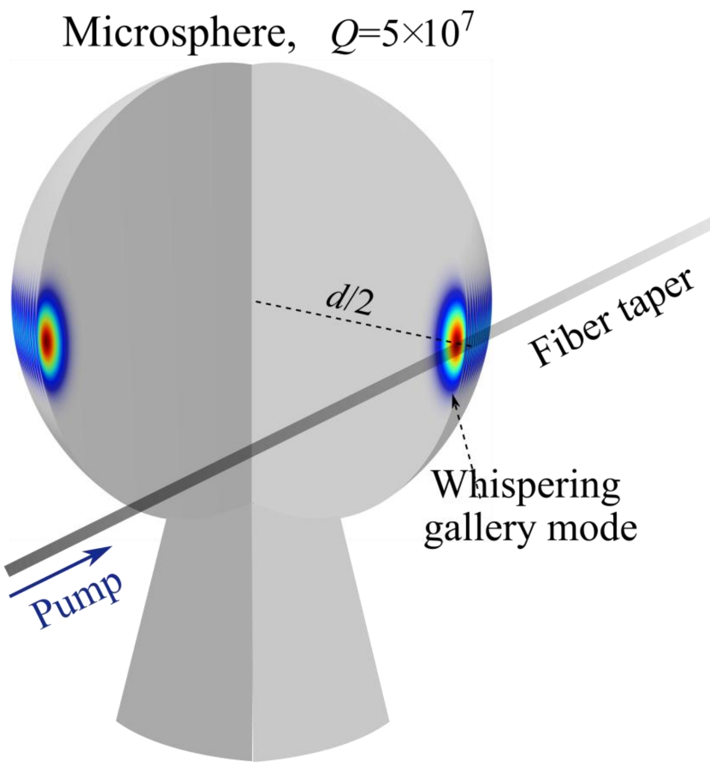
- **Acousto-optical nonlinearity**

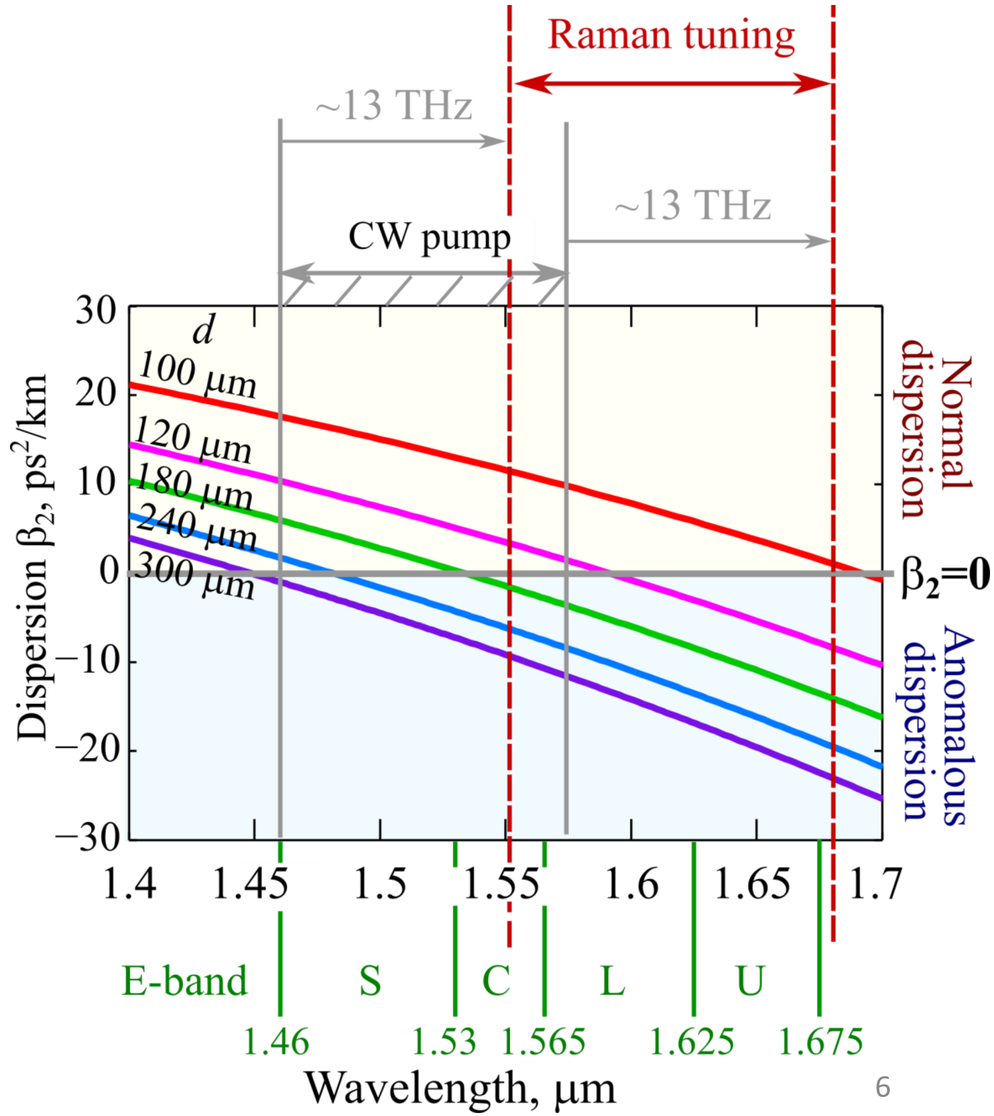
(including stimulated Brillouin scattering)



Introduction: silica microspheres made of standard telecom fiber

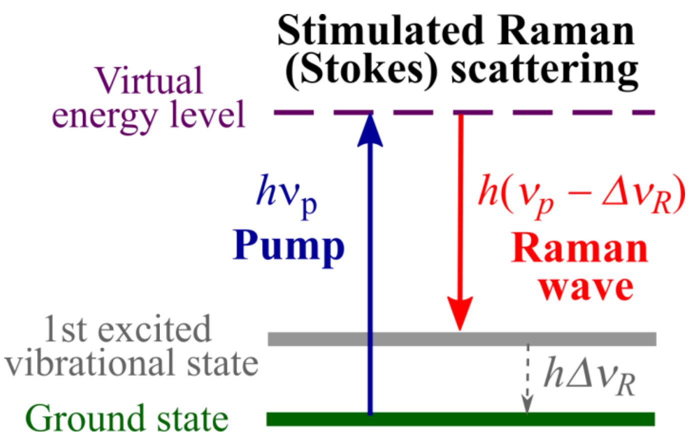






Introduction: Raman lasing in microresonators

Inelastic SRS



Raman lasing in high-Q microresonators is achieved at wavelengths inside and outside gain bands of laser media.

$$P_{thresh} \sim \frac{V_{eff}}{g_R \times Q^2}$$

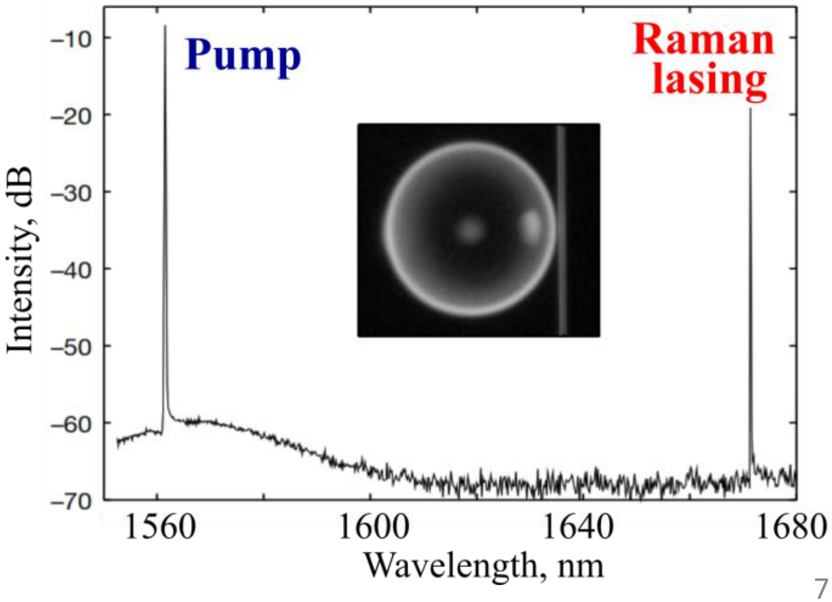
g_R – Raman gain
V_{eff} – mode volume
Q – Q-factor

- **Raman generation was reported in liquid microdroplets.**

Qian & Chang, Phys. Rev. Lett., 56, 926 (1986)

- **The first demonstration of Raman generation in a solid microresonator was in silica glass microsphere.**

Spillane, Kippenberg, Vahala, Nature, 415, 621 (2002):

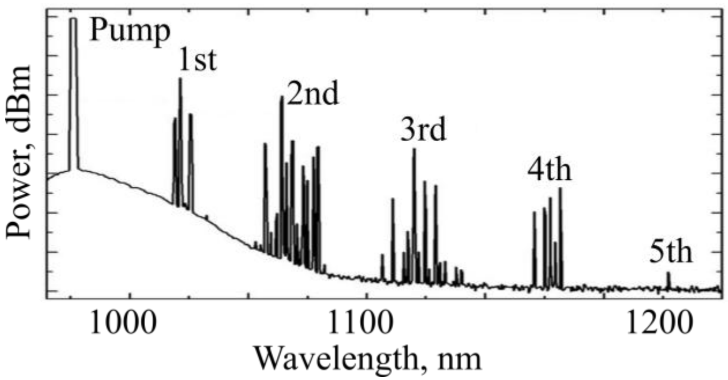


Introduction: Raman lasing in microresonators

The dynamics of intracavity radiation under the action of inelastic **stimulated Raman scattering** can be quite rich and complex even in **silica microresonators**.

- **Multicascade Raman lasing**

Min, Kippenberg, Vahala, Opt. Lett. 28, 1507 (2003):

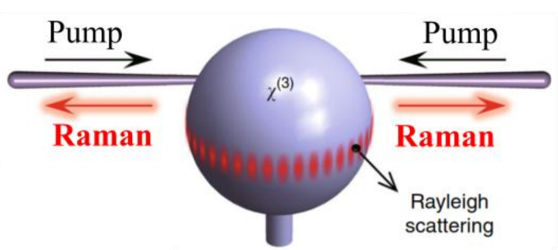


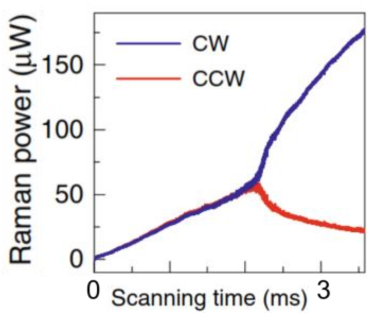
Experiment
+
theory

- **Symmetry-broken Raman laser**

Experiment

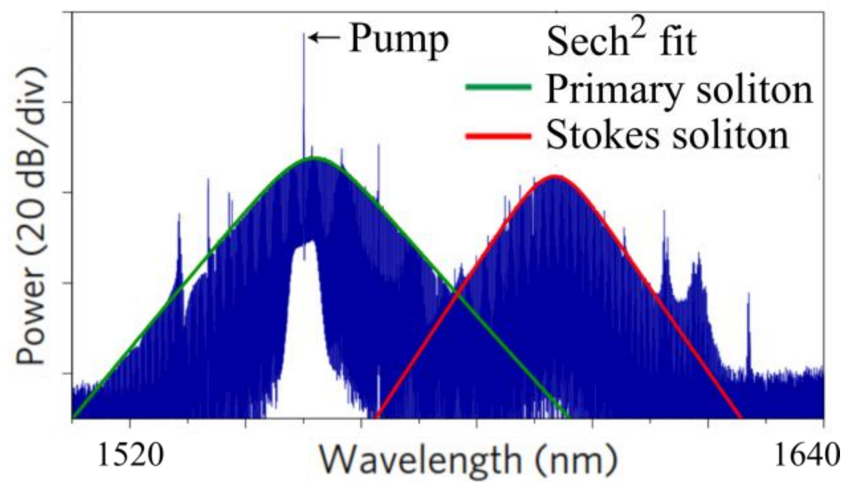
Cao et al., Nat. Commun, 11, 11366 (2020):





- **Stokes soliton held in the potential of a dissipative Kerr soliton**

Yang, Yang, Vahala, Nat. Phys. 13, 53 (2017):

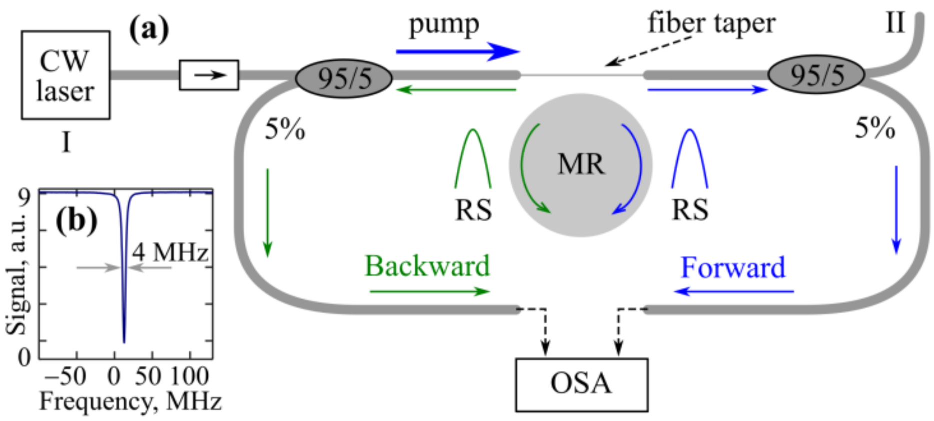


Experiment
+
theory

Symmetric Raman lasing in a silica microsphere

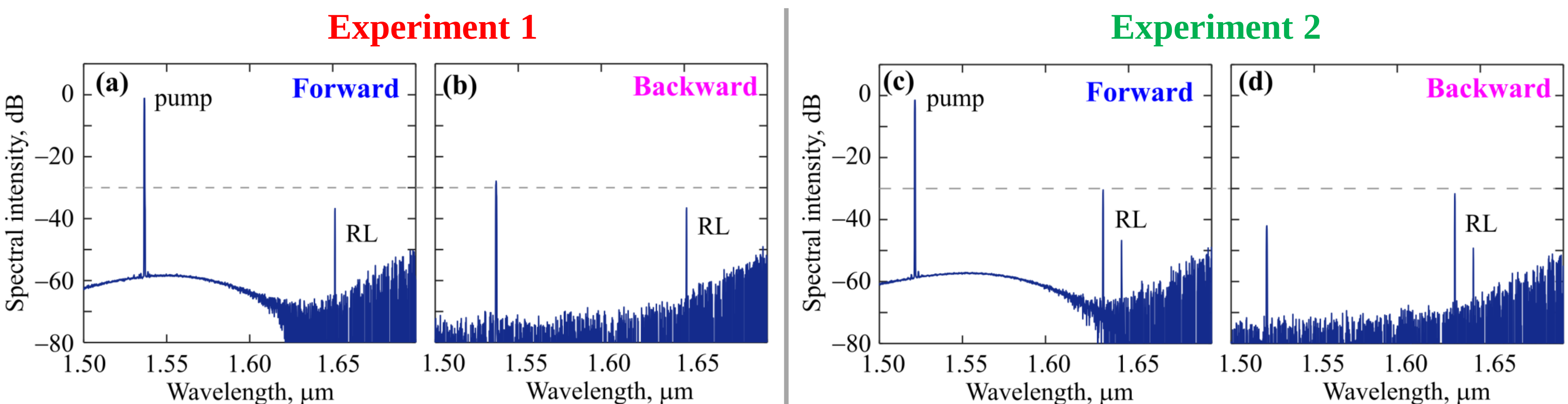
Raman gain from CW pump is known to be the same in both directions [*]

[*] G.P. Agrawal. Nonlinear Fiber Optics, 6th ed.; Elsevier: London, UK, 2019



(a) Simplified experimental scheme. MR – microresonator with whispering gallery modes; OSA – optical spectrum analyzer; RS – Raman soliton.
(b) Typical linear resonance dip near WGM

Andrianov & Anashkina, Opt. Lett. 49, 2301 (2024)

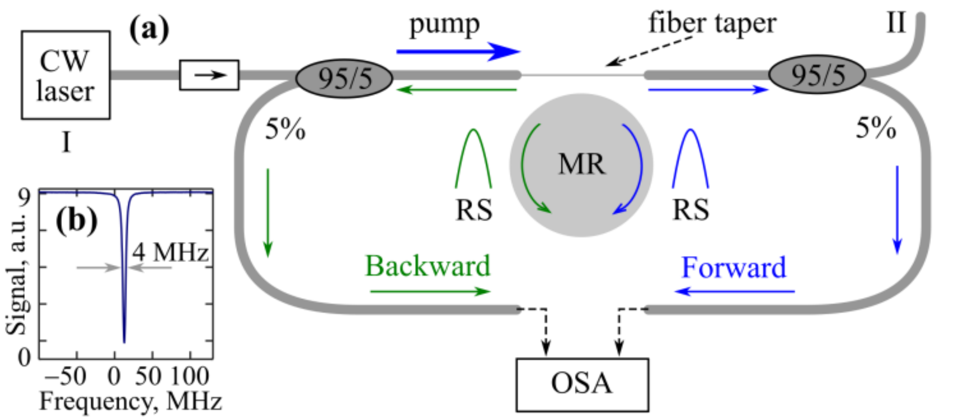


Experimental spectra demonstrating single-wavelength Raman lasing (RL) in forward **(a)** and backward **(b)** directions relative to the pump direction as well as dual-wavelength Raman lasing in forward **(c)** and backward **(d)** directions. Horizontal dashed lines at the –30 dB level are drawn for easy comparison of the corresponding spectral features in subplots **(a)** and **(b)** as well as in **(c)** and **(d)**.

Symmetric Raman lasing in a silica microsphere

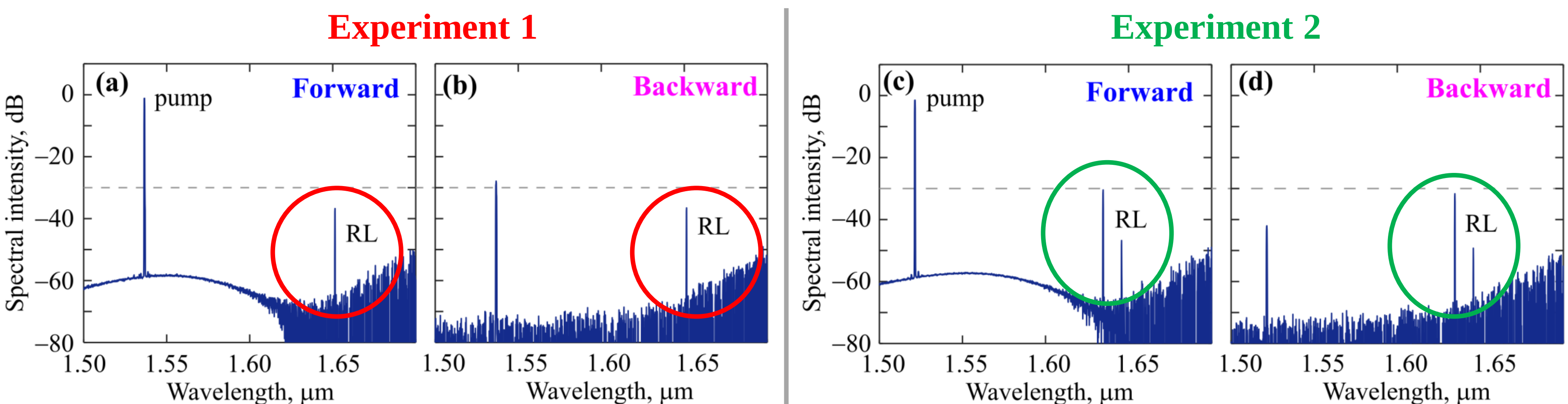
Raman gain from CW pump is known to be the same in both directions [*]

[*] G.P. Agrawal. Nonlinear Fiber Optics, 6th ed.; Elsevier: London, UK, 2019



(a) Simplified experimental scheme. MR – microresonator with whispering gallery modes; OSA – optical spectrum analyzer; RS – Raman soliton.
(b) Typical linear resonance dip near WGM

Andrianov & Anashkina, Opt. Lett. 49, 2301 (2024)

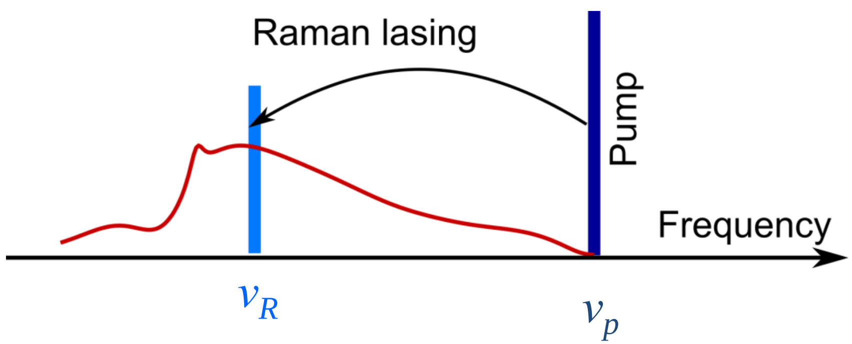


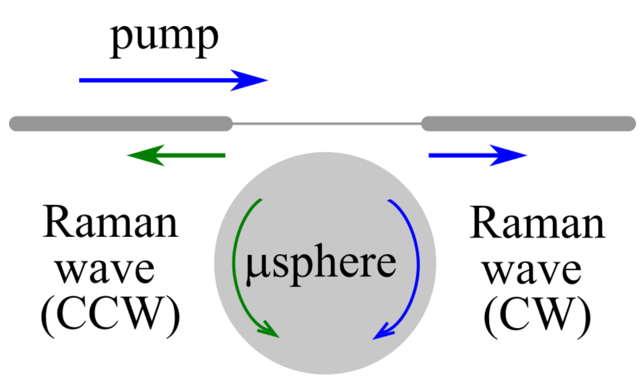
Experimental spectra demonstrating single-wavelength Raman lasing (RL) in forward **(a)** and backward **(b)** directions relative to the pump direction as well as dual-wavelength Raman lasing in forward **(c)** and backward **(d)** directions. Horizontal dashed lines at the –30 dB level are drawn for easy comparison of the corresponding spectral features in subplots **(a)** and **(b)** as well as in **(c)** and **(d)**.

Bidirectional symmetric Raman waves: theory

Evolution of the wave at the pump frequency:
- Continuous-wave pump
- Loss (limited Q-factor)
- Frequency detuning from the exact resonance
- Raman nonlinearity (loss to Raman wave amplification)
- Kerr self-phase modulation
- Kerr cross-phase modulation

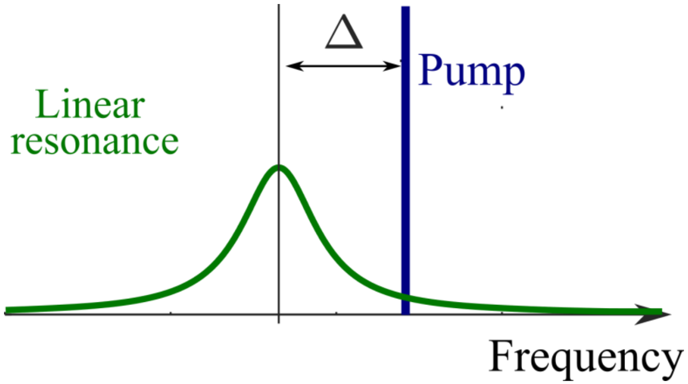
Evolution of Raman waves:
- Loss (limited Q-factor)
- Raman nonlinearity (amplification by wave at the pump frequency)
- Kerr self-phase modulation
- Kerr cross-phase modulation



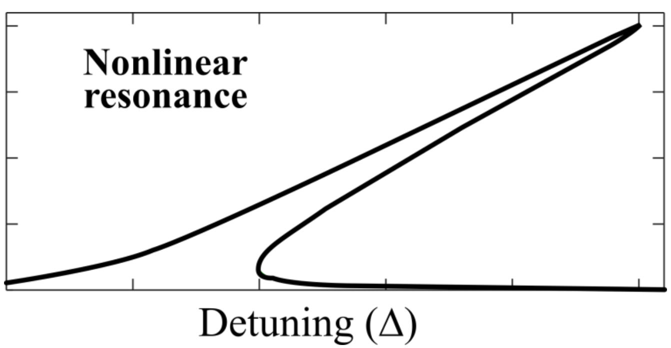


Raman gain from CW pump is the same in both directions

CW Raman lasing

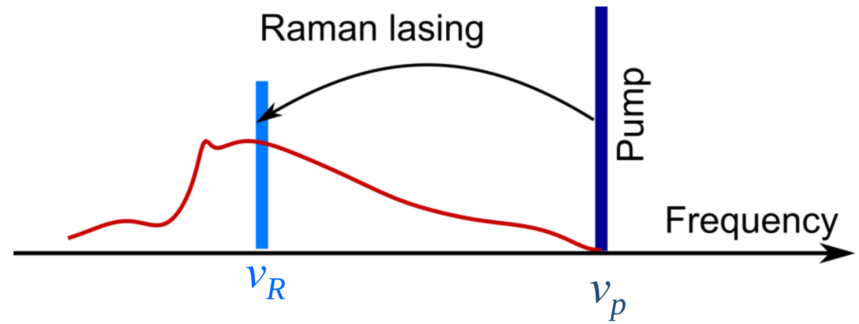


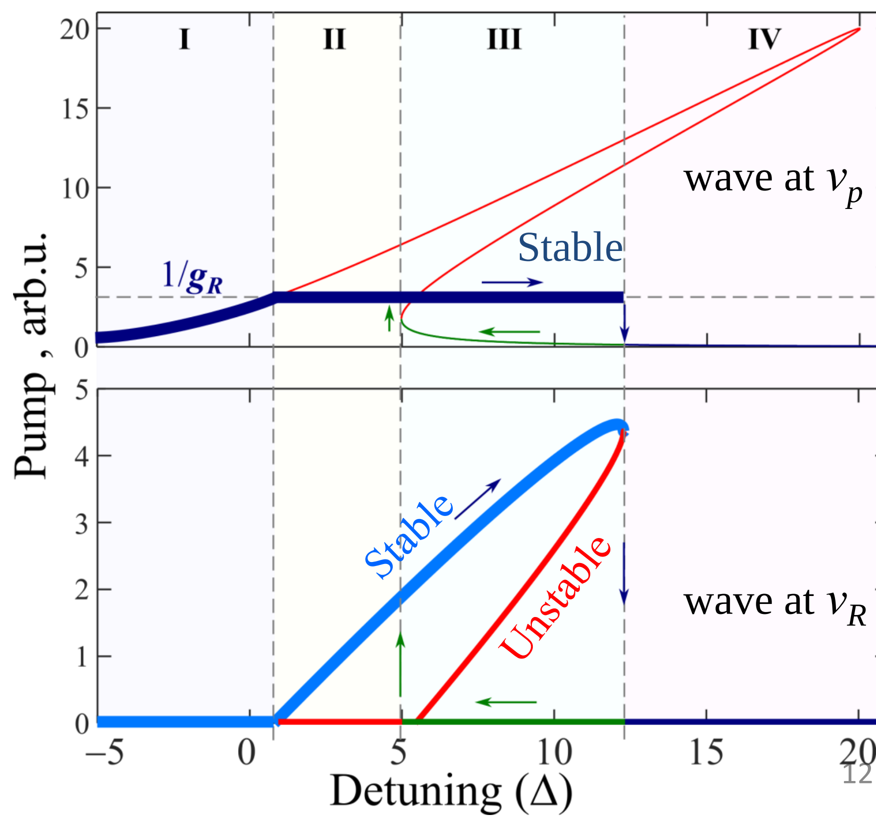
Only Kerr nonlinearity:



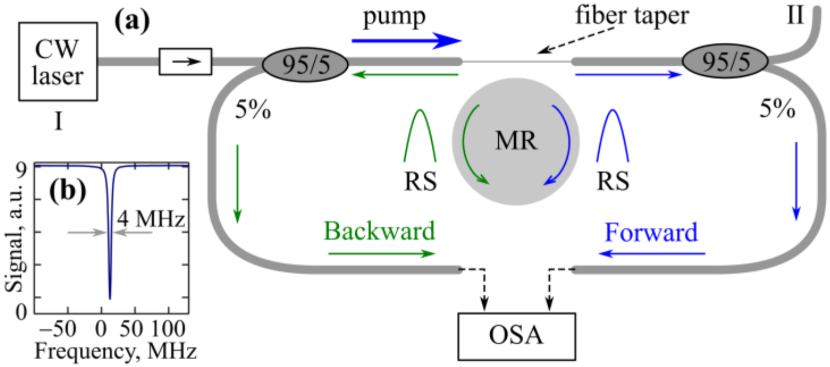
Δ is the dimensionless detuning of the pump frequency from the exact resonance (in resonance widths)

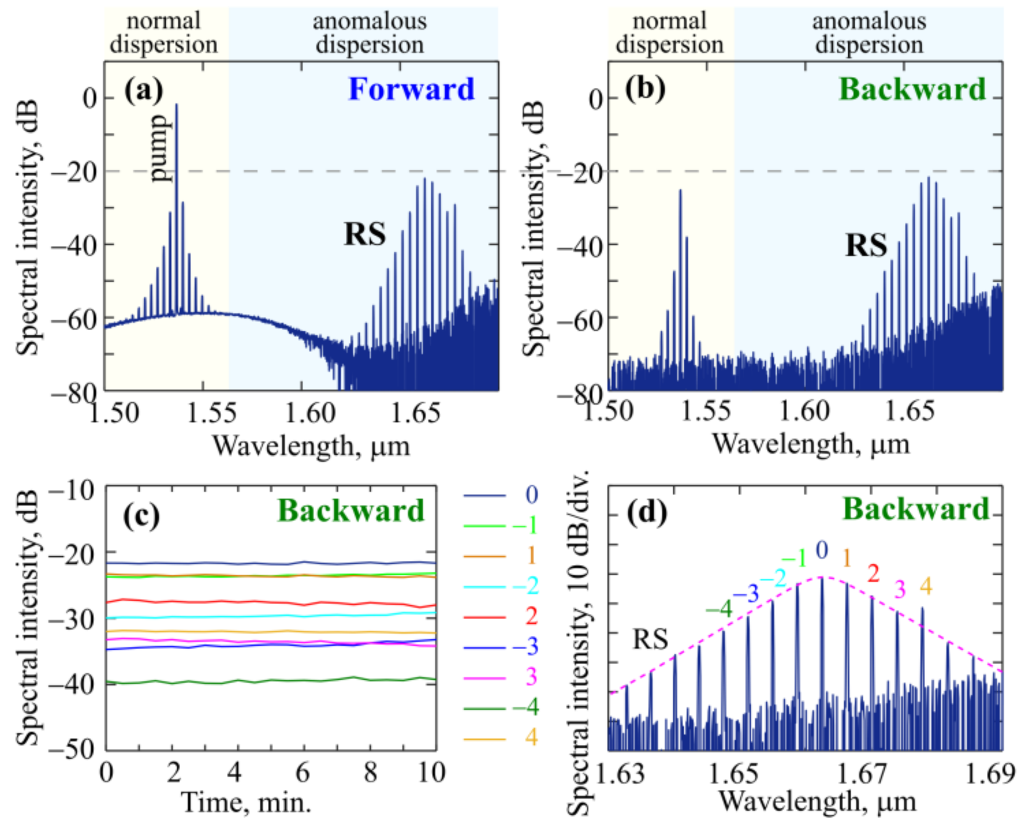
Stationary symmetric states with Raman lasing:





Bidirectional symmetric Raman soliton-like combs with unidirectional pump



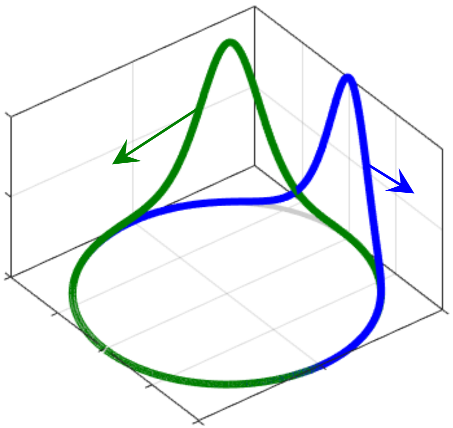


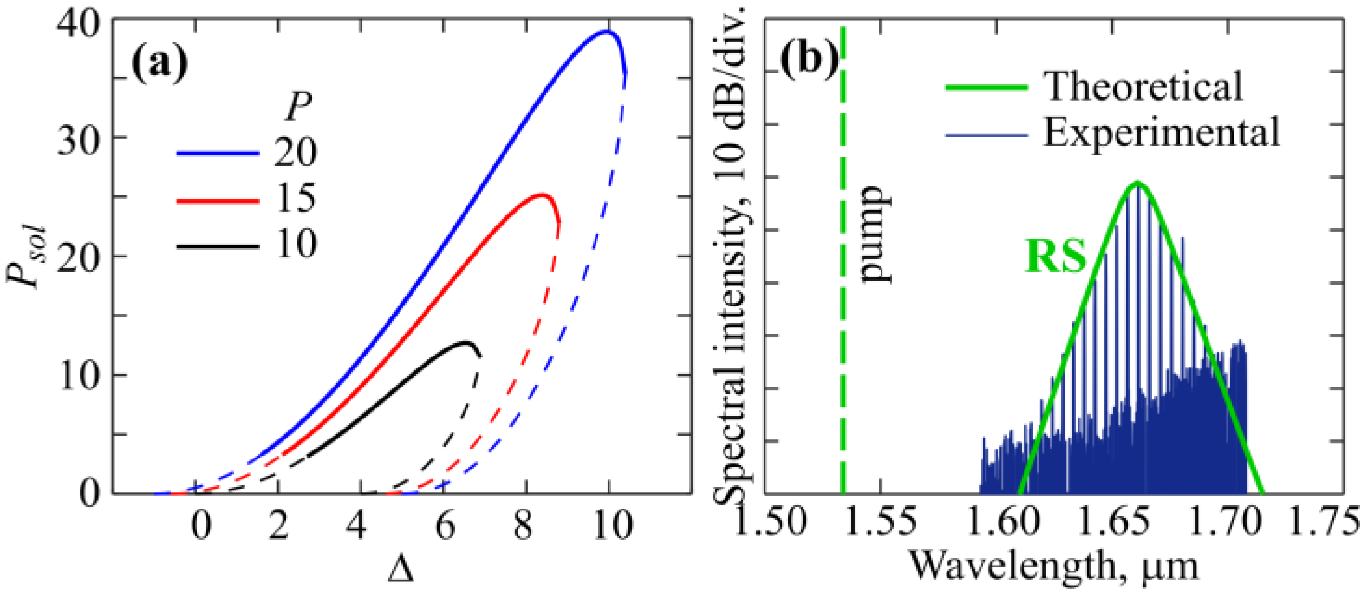
We have experimentally demonstrate bidirectional symmetric Raman soliton-like combs in a WGM microresonator with unidirectional pump, for the first time, to the best of our knowledge.

Andrianov & Anashkina, Opt. Lett. 49, 2301 (2024)

Experimental spectra demonstrating Raman solitons (RS) in forward (a) and backward (b) directions. The horizontal dashed line at the –20 dB level is drawn for easy comparison of the corresponding spectral features in subplots (a) and (b). (c) Spectral intensity of several spectral lines of the backward-propagating soliton as a function of time. (d) Zoomed-in spectrum of backward-propagating solitons (solid dark blue) and sech2-shaped envelope (dotted magenta).

Bidirectional symmetric Raman soliton-like combs with unidirectional pump: theory





(a) Theoretical soliton peak power versus pump detuning for different pump powers. Solid lines correspond to stable solitons and dashed lines correspond to unstable solutions.
(b) Theoretical spectrum envelope of Raman soliton for P_{sol} = 9.3 in comparison with experimental Raman spectrum.

Andrianov & Anashkina,
Opt. Lett. 49, 2301 (2024)

Bidirectional symmetric Raman soliton-like combs with unidirectional pump: analytical approach

Evolution of the wave at the pump frequency:

$$\frac{\partial A_{1p}}{\partial t} = \sqrt{P} - (1 + i\Delta)A_{1p} - g_R \frac{\omega_p}{\omega_R}(\langle |A_{1R}|^2\rangle + \langle |A_{2R}^{(r)}|^2\rangle)A_{1p} + i|A_{1p}|^2 A_{1p} + 2i(\langle |A_{1R}|^2\rangle + \langle |A_{2R}^{(r)}|^2\rangle)A_{1p}$$

Evolution Pump Loss Detuning Raman NL Kerr SPM Kerr XPM

Evolution of the Raman waves:

$$\frac{\partial A_{1R}}{\partial t} = -A_{1R} + g_R|A_{1p}|^2 A_{1R} - i\frac{\beta_2}{2}\frac{\partial^2 A_{1R}}{\partial \theta^2} + i|A_{1R}|^2 A_{1R} + 2i(|A_{1p}|^2 + \langle |A_{2R}^{(r)}|^2\rangle)A_{1R},$$

$$\frac{\partial A_{2R}^{(r)}}{\partial t} = -A_{2R}^{(r)} + g_R|A_{1p}|^2 A_{2R}^{(r)} - i\frac{\beta_2}{2}\frac{\partial^2 A_{2R}^{(r)}}{\partial \theta^2} + i|A_{2R}^{(r)}|^2 A_{2R}^{(r)} + 2i(|A_{1p}|^2 + \langle |A_{1R}|^2\rangle)A_{2R}^{(r)},$$

Evolution Loss Raman NL Dispersion Kerr SPM Kerr XPM

We have found solution with symmetric Ramam solitons: $|A_{1R}|^2 = |A_{2R}{}^{(r)}|^2$

$$A_{1R} = \frac{\sqrt{P_{sol}}}{\cosh(\theta/\theta_0)}\exp(i\psi t), \quad P_{sol} = |\beta_2|/\theta_0{}^2, \quad \psi = -\frac{\beta_2}{2\theta_0^2} + 2P_1 + \frac{\sqrt{P_{sol}}\beta_2}{\pi}$$

Wave at the pump frequency: $A_{1p} = const$, $|A_{1p}|^2 = P_1$, $P_1 = 1/g_R$

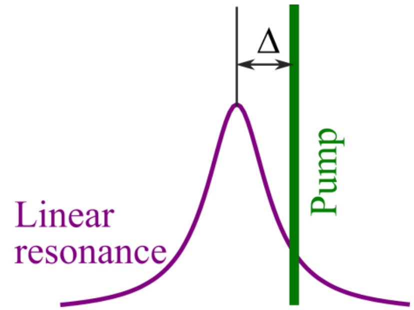
Moving to “symmetry broken” states

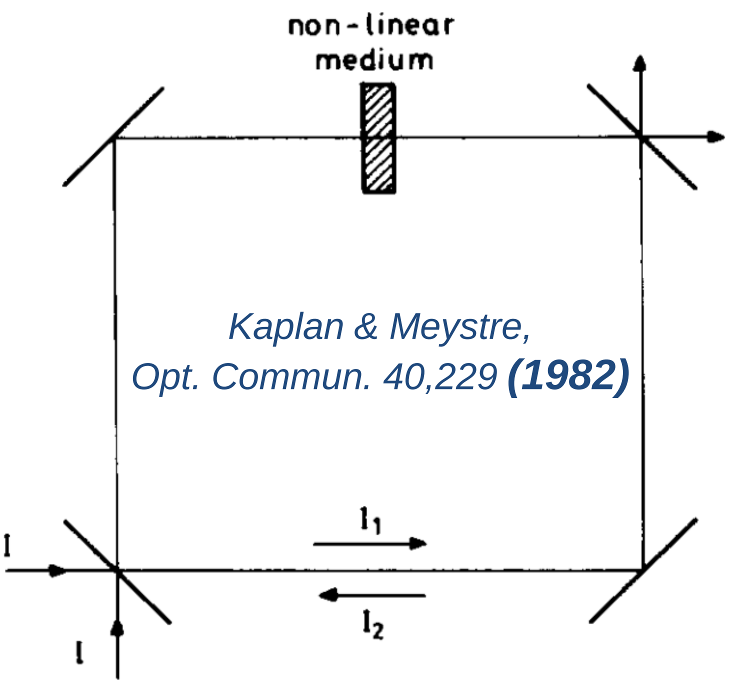
Auxiliary: spontaneous symmetry breaking (SSB) for only Kerr nonlinearity (well-known)

$$\frac{dA_1}{dt} = -A_1 - i\Delta \cdot A_1 + i|A_1|^2 A_1 + 2i|A_2|^2 A_1 + \sqrt{X}$$

$$\frac{dA_2}{dt} = -A_2 - i\Delta \cdot A_2 + i|A_2|^2 A_2 + 2i|A_1|^2 A_2 + \sqrt{X}$$

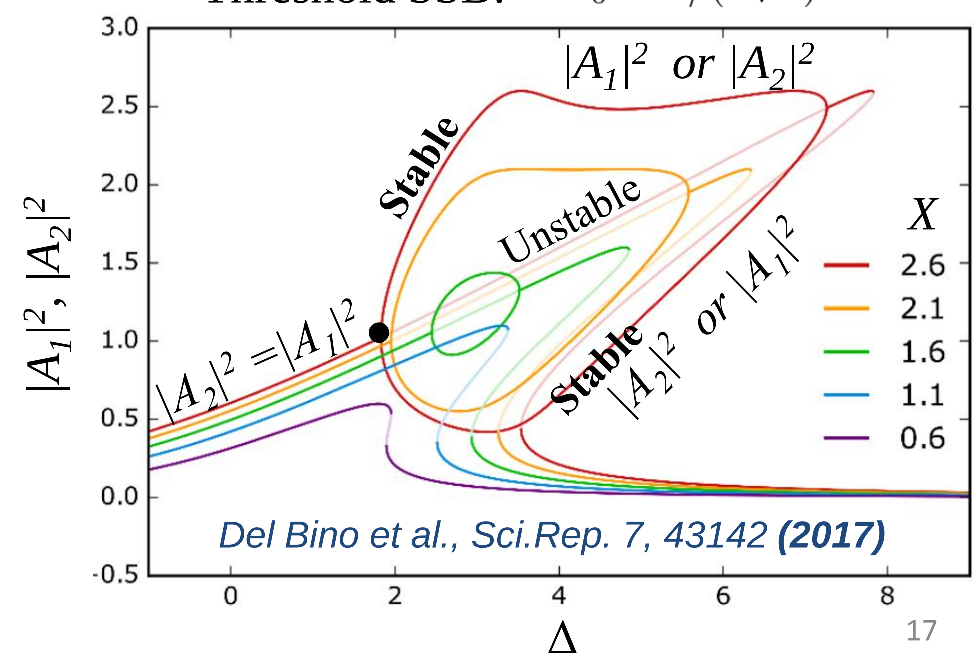
Loss — Frequency detuning — Kerr self-phase modulation — Kerr cross-phase modulation — Pump





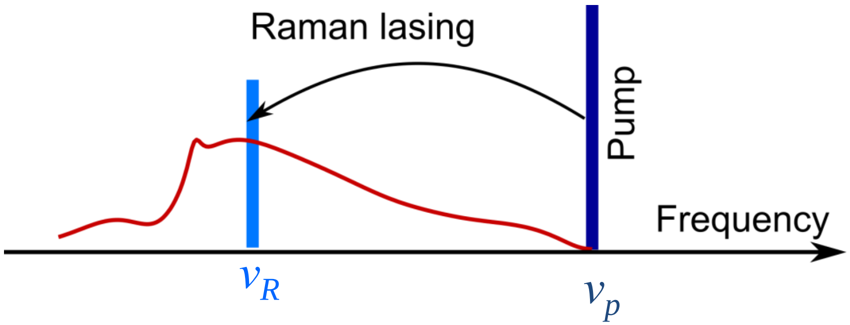
Kaplan & Meystre, Opt. Commun. 40,229 ***(1982)***

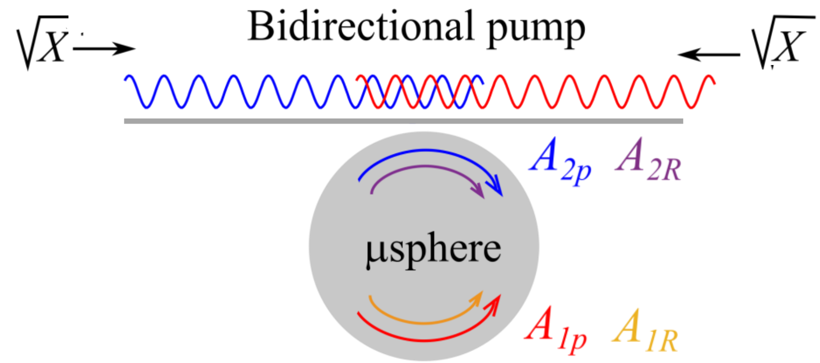
Threshold SSB: $X_0 = 8/(3\sqrt{3}) \approx 1.54$



Del Bino et al., Sci.Rep. 7, 43142 ***(2017)***

Theoretical study of "symmetry broken" states of Raman waves





Equations for waves at pump frequency ν_p:

$$\frac{dA_{2p}}{dt} = (-1 - i\Delta)A_{2p} + i\left[\left(2|A_{1p}|^2 + |A_{2p}|^2\right) + \left(2|A_{1R}|^2 + 2|A_{2R}|^2\right)\right]A_{2p} - g_R\frac{\omega_p}{\omega_R}\left(|A_{1R}|^2 + |A_{2R}|^2\right)A_{2p} + i\beta A_{1p} + \sqrt{X}$$

$$\frac{dA_{1p}}{dt} = (-1 - i\Delta)A_{1p} + i\left[\left(|A_{1p}|^2 + 2|A_{2p}|^2\right) + \left(2|A_{1R}|^2 + 2|A_{2R}|^2\right)\right]A_{1p} - g_R\frac{\omega_p}{\omega_R}\left(|A_{1R}|^2 + |A_{2R}|^2\right)A_{1p} + i\beta A_{2p} + \sqrt{X}$$

Loss, Frequency detuning, Kerr self-phase modulation, Kerr cross-phase modulation, Raman NL, Rayleigh scattering, Pump

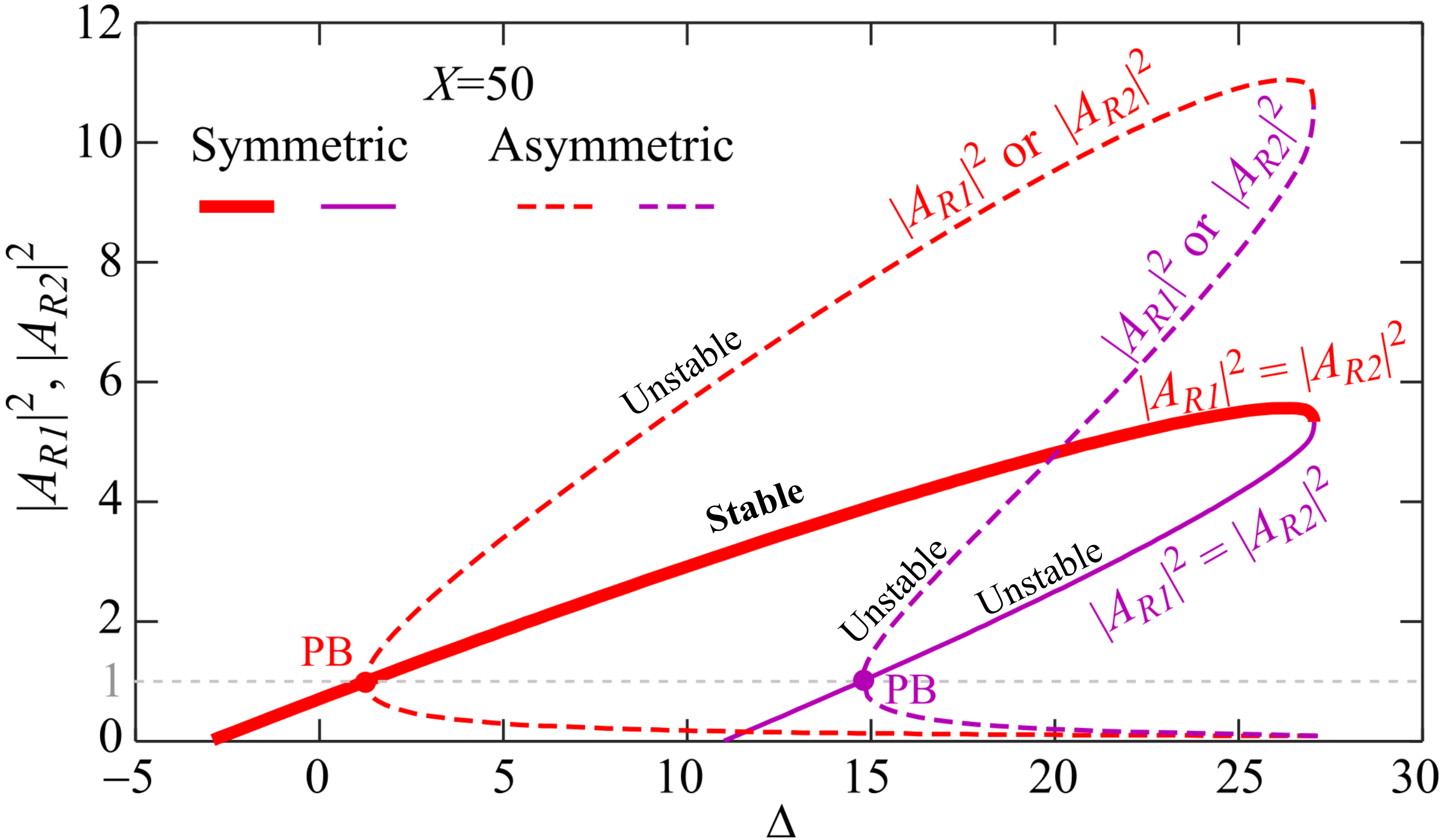
Equations for Raman waves at ν_R:

$$\frac{dA_{1R}}{dt} = -A_{1R} + i\left[\left(2|A_{1p}|^2 + 2|A_{2p}|^2\right) + \left(|A_{1R}|^2 + 2|A_{2R}|^2\right)\right]A_{1R} + g_R\left(|A_{1p}|^2 + |A_{2p}|^2\right)A_{1R} + i\beta A_{2R}$$

$$\frac{dA_{2R}}{dt} = -A_{2R} + i\left[\left(2|A_{1p}|^2 + 2|A_{2p}|^2\right) + \left(2|A_{1R}|^2 + |A_{2R}|^2\right)\right]A_{2R} + g_R\left(|A_{1p}|^2 + |A_{2p}|^2\right)A_{2R} + i\beta A_{1R}$$

Loss, Kerr cross-phase modulation, Kerr self-phase modulation, Raman NL, Rayleigh scattering

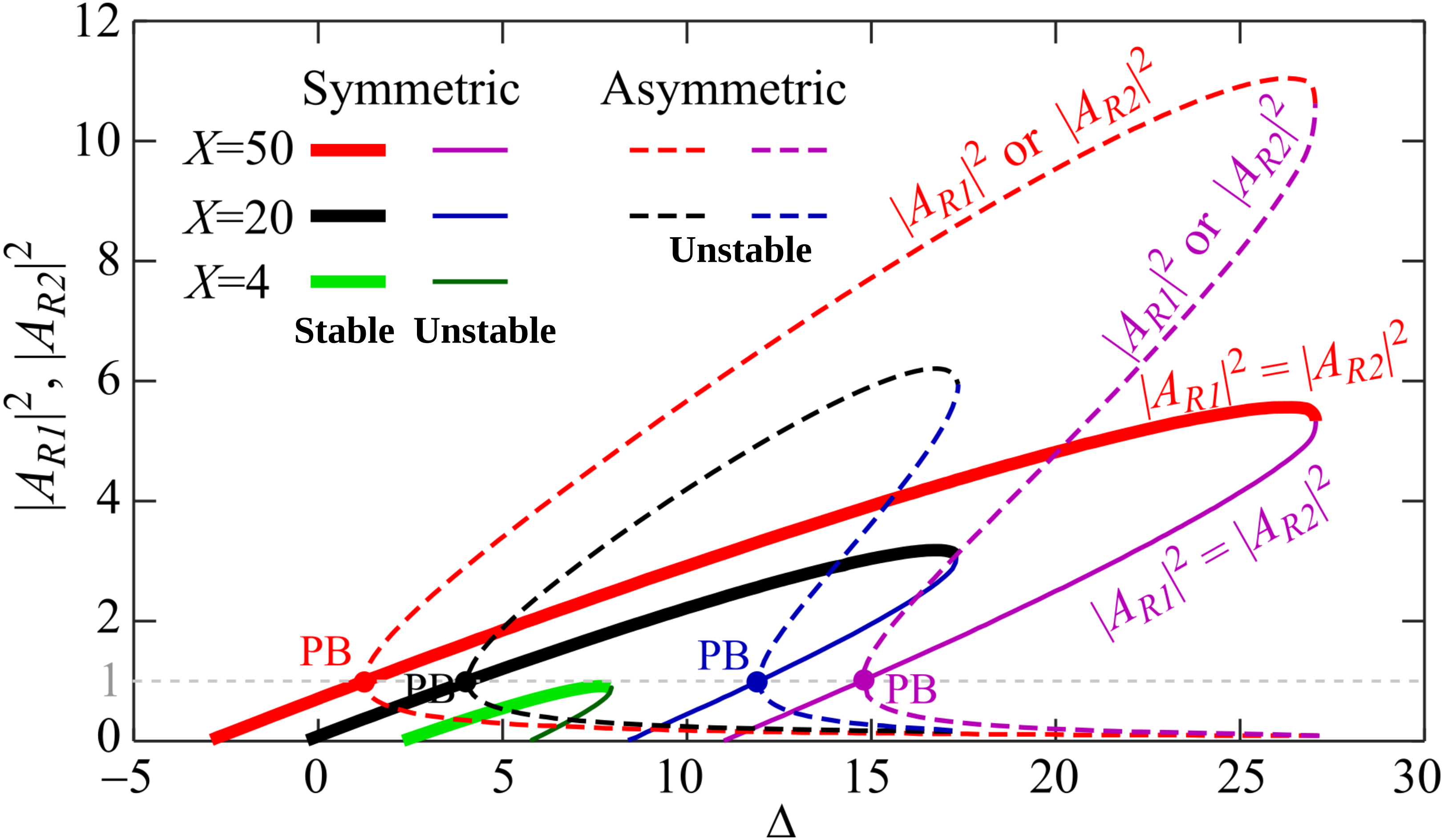
Stationary states for Raman lasing (theoretical)



Symmetric and asymmetric stationary states of Raman wave intensities $|A_{R1}|^2$ and $|A_{R2}|^2$ theoretically found for X = 50. PB – pitchfork bifurcation

Andrianov, Anashkina, Opt. Lett. 50, 495 (2025)

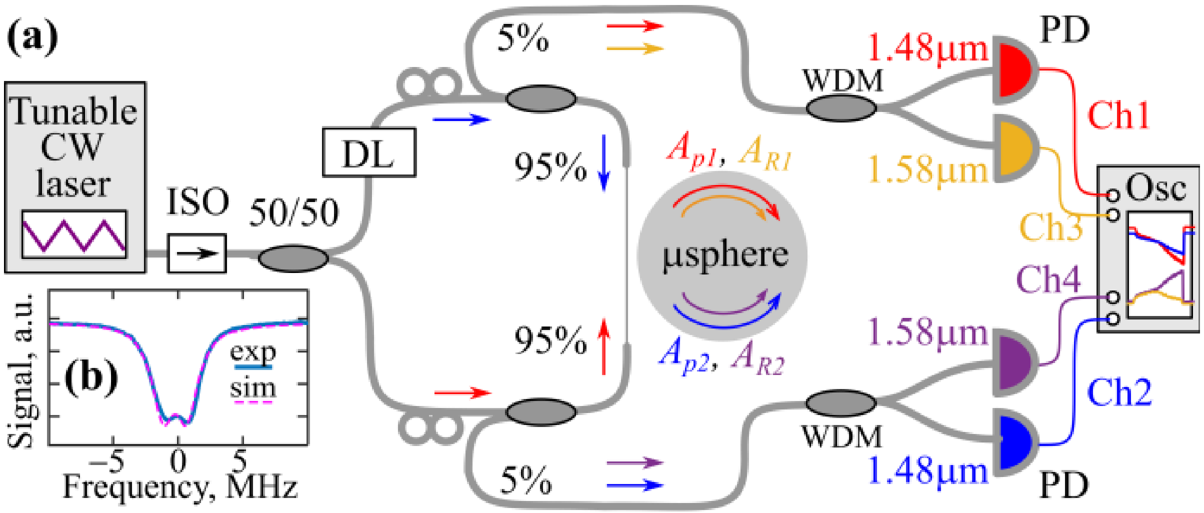
Stationary states for Raman lasing (theoretical)



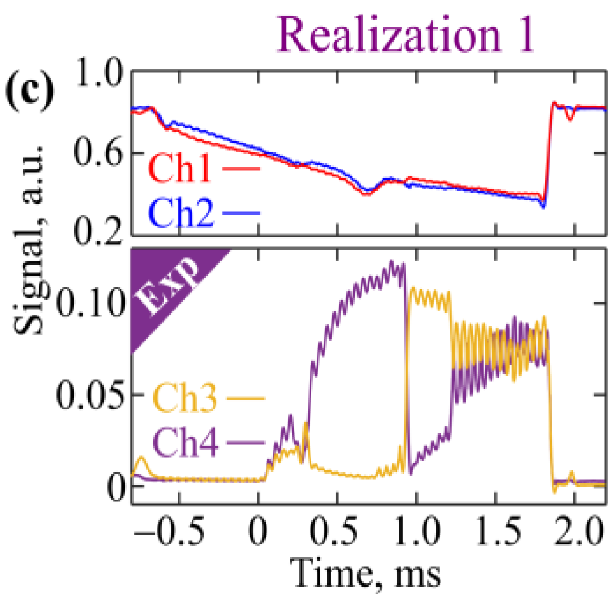
Symmetric and asymmetric stationary states of Raman wave intensities $|A_{R1}|^2$ and $|A_{R2}|^2$ theoretically found for different X. PB – pitchfork bifurcation

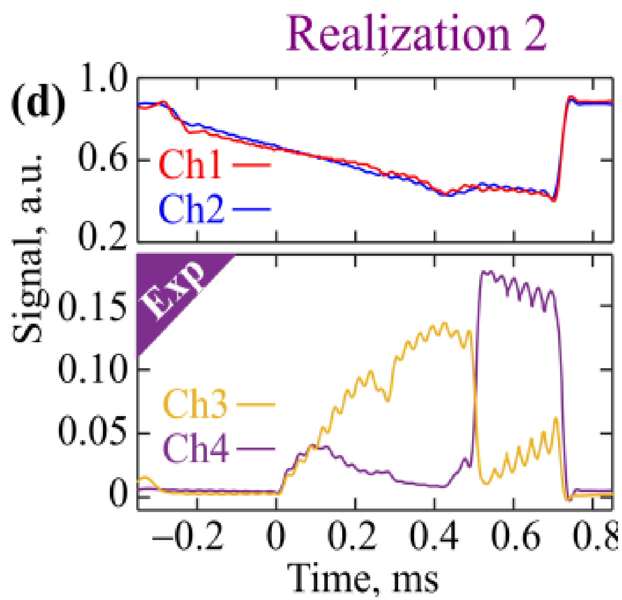
Andrianov, Anashkina, Opt. Lett. 50, 495 (2025)

Experimental results



(a) Simplified experimental scheme. ISO – Faraday isolator; DL – adjustable delay line; WDM – wavelength division multiplexer; PD – photodiode; Ch1-4 – channels 1-4; Osc – oscilloscope.
(b) Measured and simulated (at $\beta = 1$) linear resonance for unidirectional pump (<0.1 mW).





(c, d) Experimental signals measured in channels 1-4 while sweeping the pump frequency for two different realizations; laser power was 9 mW **(c)** and 9.5 mW **(d)**.

Andrianov, Anashkina, Opt. Lett. 50, 495 (2025)

How to explain experimental results…

We have propose an explanation based on back reflection of a single Raman wave, possible due to a defect on the tapered fiber or other scheme element (fiber splices, fiber components, etc).

$$\frac{dA_{2p}}{dt} = (-1 - i\Delta)A_{2p} + i\left[\left(2|A_{1p}|^2 + |A_{2p}|^2\right) + \left(2|A_{1R}|^2 + 2|A_{2R}|^2\right)\right]A_{2p} - g_R\frac{\omega_p}{\omega_R}\left(|A_{1R}|^2 + |A_{2R}|^2\right)A_{2p} + i\beta A_{1p} + \sqrt{X}$$

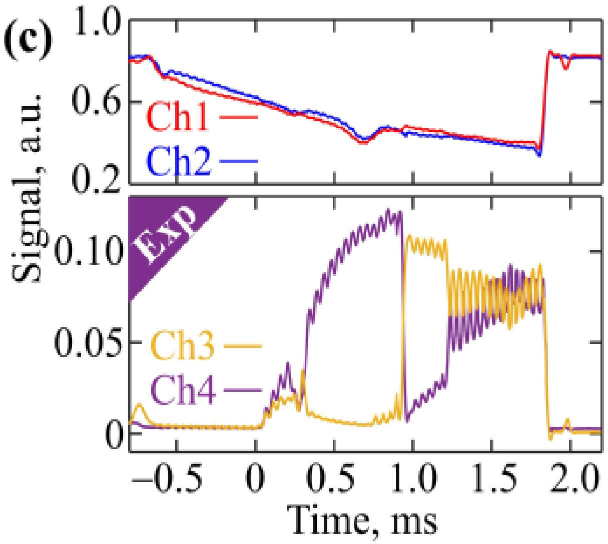
$$\frac{dA_{1p}}{dt} = (-1 - i\Delta)A_{1p} + i\left[\left(|A_{1p}|^2 + 2|A_{2p}|^2\right) + \left(2|A_{1R}|^2 + 2|A_{2R}|^2\right)\right]A_{1p} - g_R\frac{\omega_p}{\omega_R}\left(|A_{1R}|^2 + |A_{2R}|^2\right)A_{1p} + i\beta A_{2p} + \sqrt{X}$$

$$\frac{dA_{1R}}{dt} = -A_{1R} + i\left[\left(2|A_{1p}|^2 + 2|A_{2p}|^2\right) + \left(|A_{1R}|^2 + 2|A_{2R}|^2\right)\right]A_{1R} + g_R\left(|A_{1p}|^2 + |A_{2p}|^2\right)A_{1R} + i\beta A_{2R}$$

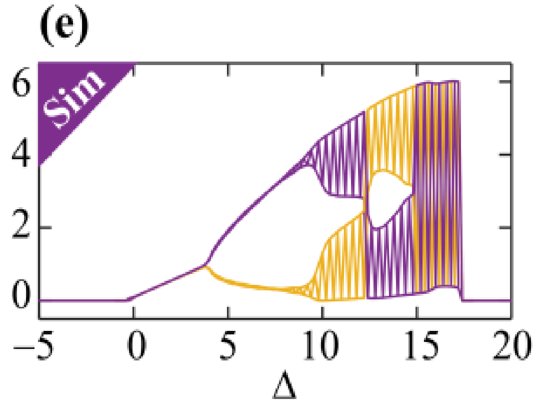
$$\frac{dA_{2R}}{dt} = -A_{2R} + i\left[\left(2|A_{1p}|^2 + 2|A_{2p}|^2\right) + \left(2|A_{1R}|^2 + |A_{2R}|^2\right)\right]A_{2R} + g_R\left(|A_{1p}|^2 + |A_{2p}|^2\right)A_{2R} + i\beta A_{1R} + \varepsilon A_{1R}e^{i\theta}$$

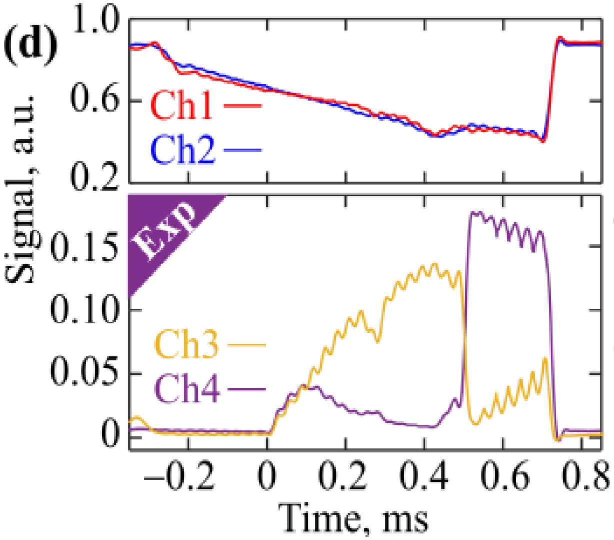
ε is the small coefficient of the back reflection and ξ is the phase

Experiments vs. numerical simulations

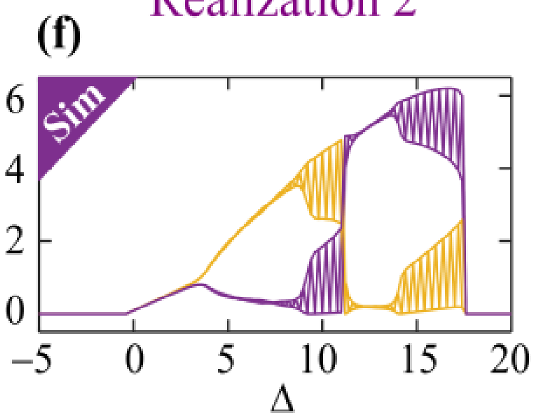


Realization 1





Realization 2

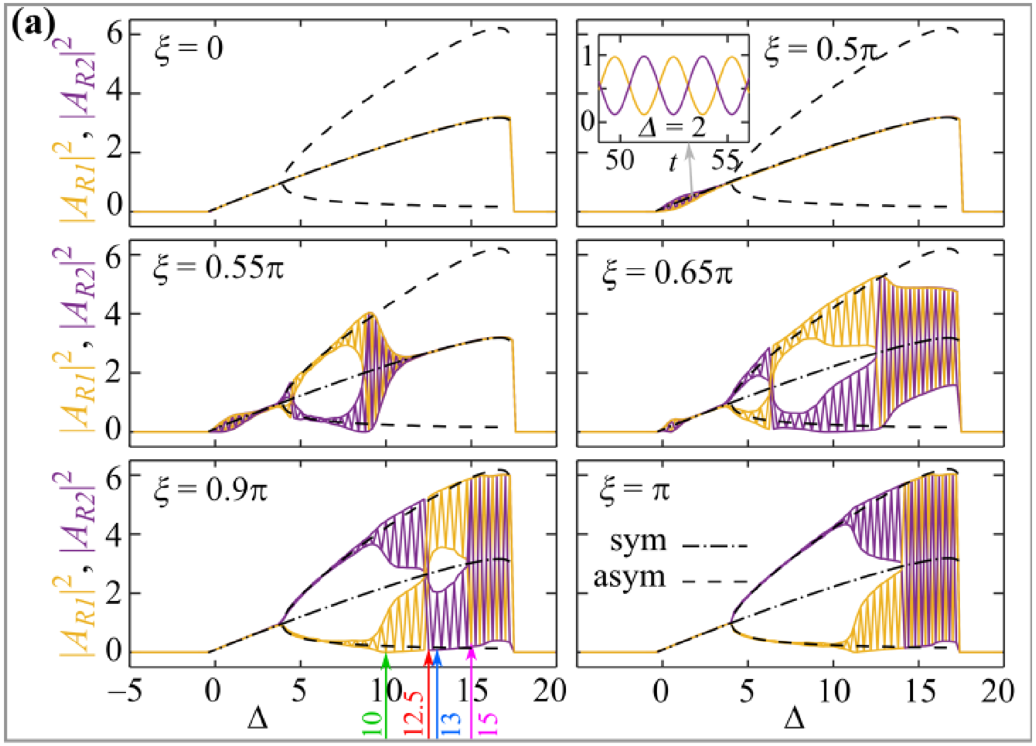


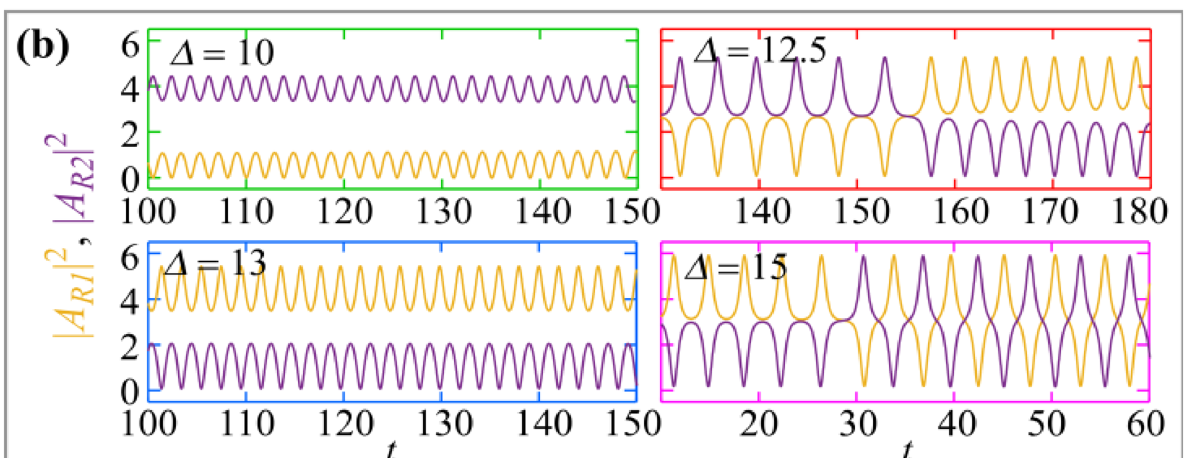
(c, d) Experimental signals measured in channels 1-4 while sweeping the pump frequency for two different realizations; laser power was 9 mW **(c)** and 9.5 mW **(d)**.

Raman wave intensities $|A_{R1}|^2$ and $|A_{R2}|^2$ numerically simulated at X = 20 for increasing Δ for ε = 0.01, ξ = 0.9π **(e)** and for ε = 0.025 ξ = −0.7π **(f)**

Andrianov, Anashkina, Opt. Lett. 50, 495 (2025)

Numerical simulations





(a) Raman wave intensities $|A_{R1}|^2$, $|A_{R2}|^2$ numerically simulated for increasing Δ for X = 20, ε = 0.01 and different ξ indicated in each panel. Dash-dotted and dashed curves correspond, respectively, to the symmetric (sym) and asymmetric (asym) stationary states. Cross-hatched areas correspond to oscillations, and envelopes show minimum and maximum intensity values. Inset in the panel for ξ = 0.5 shows oscillogram at Δ = 2.

(b) Numerically simulated oscillograms for ξ = 0.9π and different Δ. These Δs are shown in (a) by vertical colored arrows in the panel for ξ = 0.9π.

Summary

- We have experimentally found symmetric bidirectional Raman soliton-like combs in a unidirectionally pumped silica microsphere. We have proposed a simplified theoretical model and have obtained an analytical solution for forward- and backward-propagating Raman $sech^2$-shaped solitons for which losses are compensated by Raman gain from a CW pump and dispersion is compensated by Kerr nonlinearity.

- We have experimentally demonstrated symmetry-broken Raman lasing with previously unreported features such as intensity switching of counter-propagating waves and symmetry restoring during pump frequency sweeping.

- We have found theoretically symmetric and asymmetric stationary states, but asymmetric states have proven to be unstable.

- The explanation of the experimental asymmetric Raman lasing is based on a weak asymmetry in the scheme, which dramatically changes the dynamic behavior of the system. This was confirmed by numerical simulations with added back reflection for a single Raman wave.

Thank you for your attention!