



# Оптические микрорезонаторы для квантовых измерений

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16 апреля 2019

Лаборатория квантовых оптических технологий МГУ

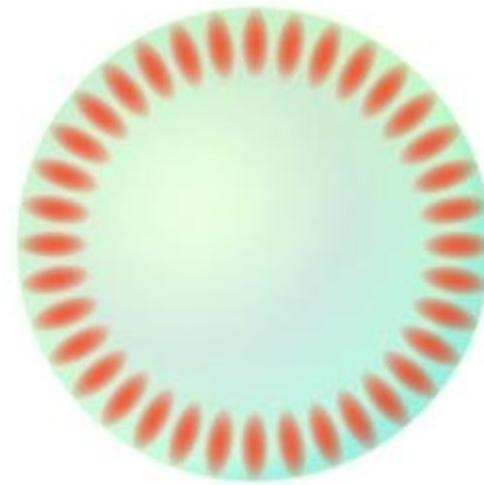
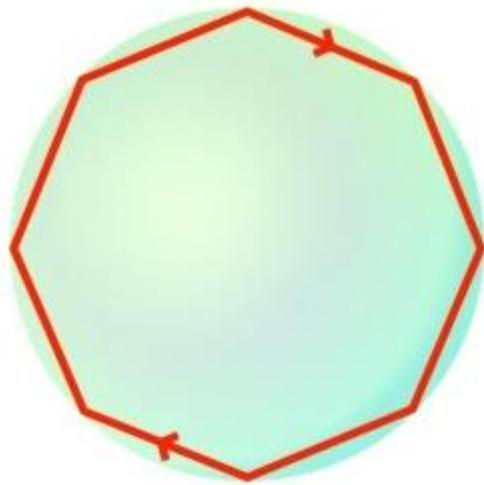
# «Шепчущая» галлерея в соборе святого Павла в Лондоне



Биленко И.А. для Лаборатории  
Квантовой Информации



# Моды шепчущей галереи в оптике



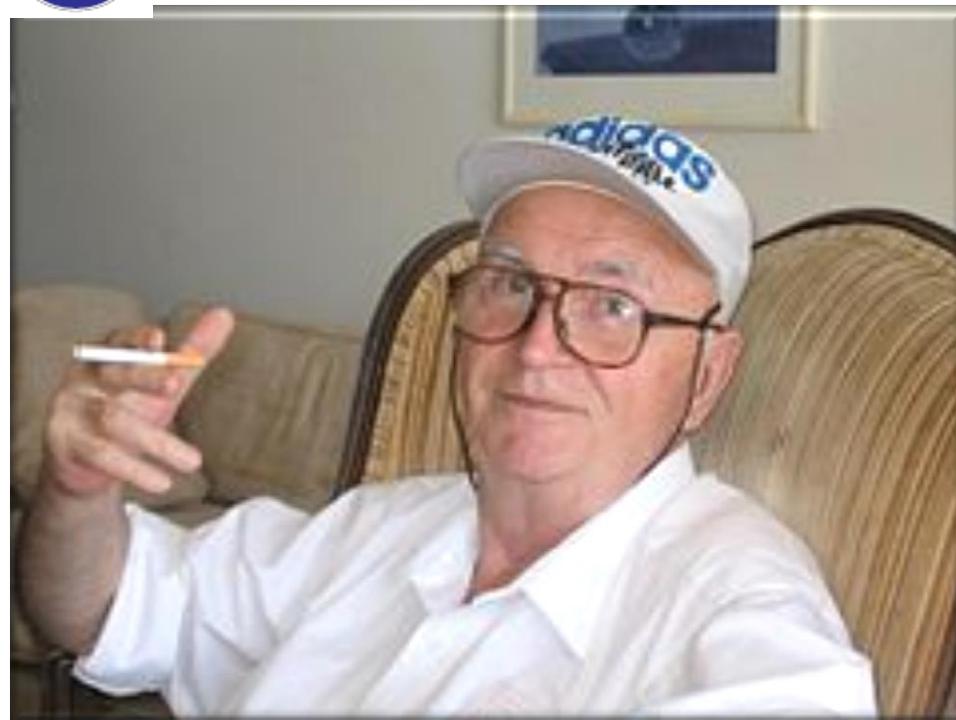
Свет распространяется вблизи поверхности – полное  
внутреннее отражение

Осьсимметричные тела, диаметр ~ 10-1000 мкм

Добротность ~  $10^7$ - $10^{11}$



# Первые высокодобротные микрорезонаторы



Профессор физического  
факультета МГУ,  
член.-корр. РАН В.Б.Брагинский  
(1931-2016)

**1986: “Мы сделали микроволновые  
резонаторы с  $Q > 10^8$ . Почему  
не попробовать в оптике?”**

$$V = 3 \cdot 5 \cdot 10^{-3} \cdot 1 \cdot 10^{-3} \cdot 3 \cdot 10^{-5} = 4 \cdot 10^{-10} \text{ см}^3 = 4 \cdot 10^{-16} \text{ м}^3$$
 Май 1986.

$$\mathcal{E} = \frac{2W \cdot Q}{\omega} = \frac{2 \cdot 0,1 \text{ мВт} \cdot 10^6}{3 \cdot 10^{15}} = \frac{2 \cdot 10 \cdot 10^6}{3 \cdot 10^{15}} = \frac{2 \cdot 10^{-6}}{3 \cdot 10^{-12}} =$$

$$W = \frac{2\pi C}{\lambda} = \frac{6 \cdot 3 \cdot 10^{10}}{7 \cdot 10^5} = 3 \cdot 10^{15}$$

$$\hbar \omega = 10^{-22} \cdot 3 \cdot 10^{15} = 3 \cdot 10^{-12}$$

$$\frac{\Sigma E^2 V}{8\pi} = \mathcal{E}; \quad E^2 = \frac{8\pi \mathcal{E}}{EV} = \frac{2 \cdot 2 \cdot 10^{-6}}{3 \cdot 4 \cdot 10^{-10}} = 4 \cdot 10^4$$

$$E = 2 \cdot 10^3 \cdot 300 = 600 \frac{\text{мВ}}{\text{м}} \Rightarrow Q = 10^6$$

$$E = 6000 \frac{\text{мВ}}{\text{м}}, \quad Q = 10^6 \text{ кратно}$$

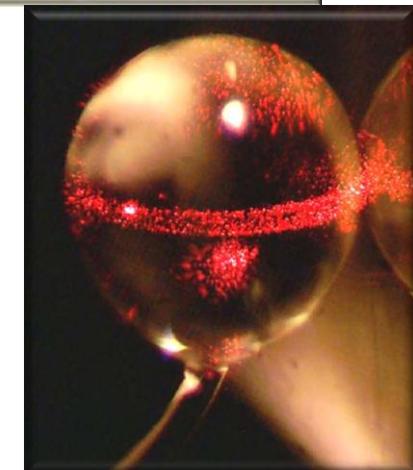
$$\left( \frac{600}{\omega_{\text{минимум}}} \right)^2 \approx 10^6 E^2 = \frac{1}{2} \cdot 10^{-13} \cdot 4 \cdot 10^4 = 2 \cdot 10^{-9}$$

Аналог  
демонстрации.

Тепловой излучение — в субмикро-частоте.  
 $C_0 \text{ ЕВ}$

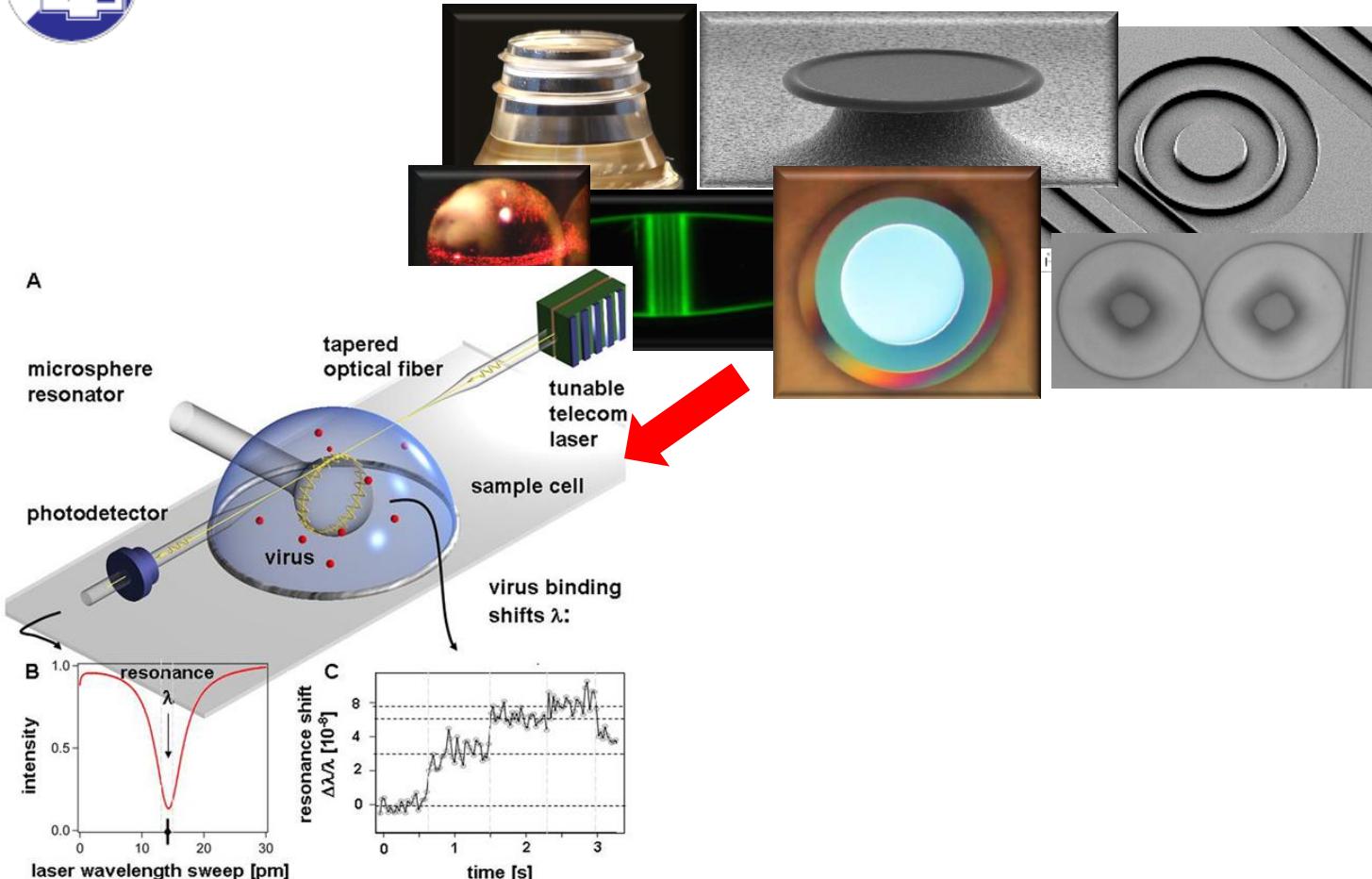
Сидящие волны!

Тепловое излучение





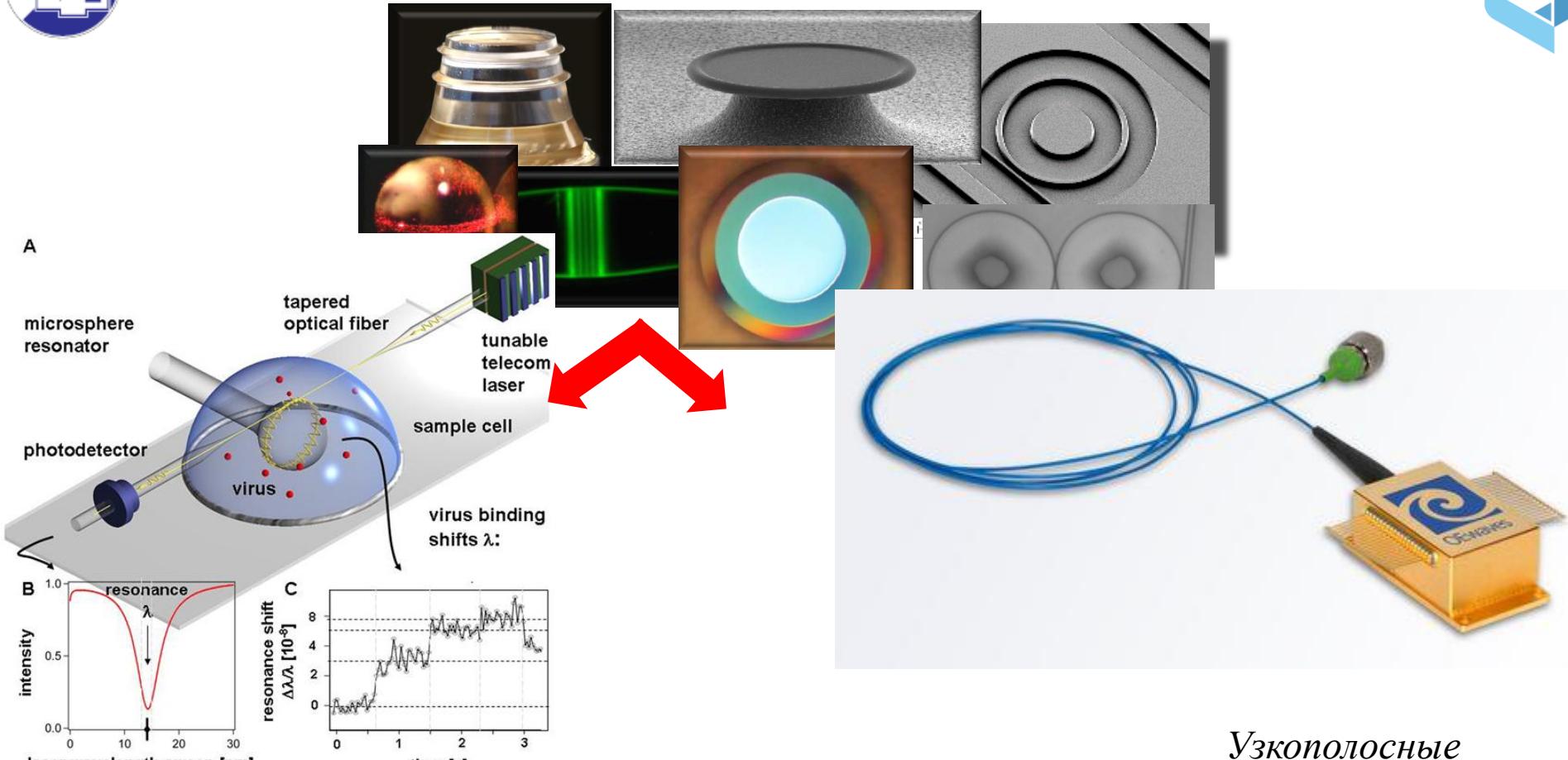
# Технологии и применения



Высокочувствительные  
сенсоры:



# Технологии и применения



Высокочувствительные  
сенсоры:

Узкополосные  
фильтры и лазеры



# Технологии и применения

A

microsphere resonator

tapered optical fiber

tunable telecom laser

photodetector

virus

B

intensity

resonance shift  $\Delta\lambda [10^{-8}]$

laser wavelength sweep [pm]

C

DKS applications

Optical frequency synthesizer

Low-noise microwaves

Optical coherence tomography

Dual-comb spectroscopy

Astronomical spectrometer calibration

Ultrafast distance measurements

Optical atomic clocks

Photonic Radar

Si<sub>3</sub>N<sub>4</sub>

MgF<sub>2</sub>

100 μm

2 mm

Radar transceiver

Photonic-based RF generator

MLL

Photonic-based ADC

Digital signal processor

Yukon poles

filters and lasers

Узкополосные фильтры и лазеры

Высокочувствительные сенсоры:

Устройства на основе оптических гребенок



# Частотные оптические гребенки

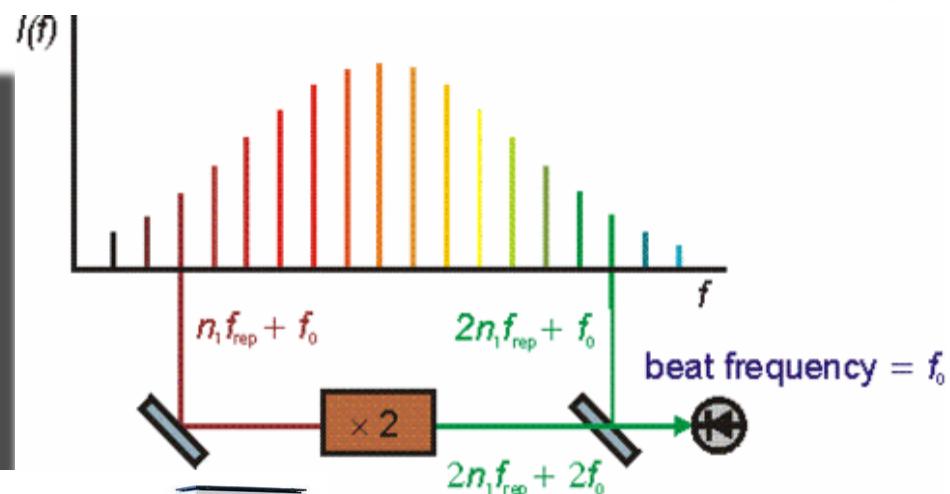
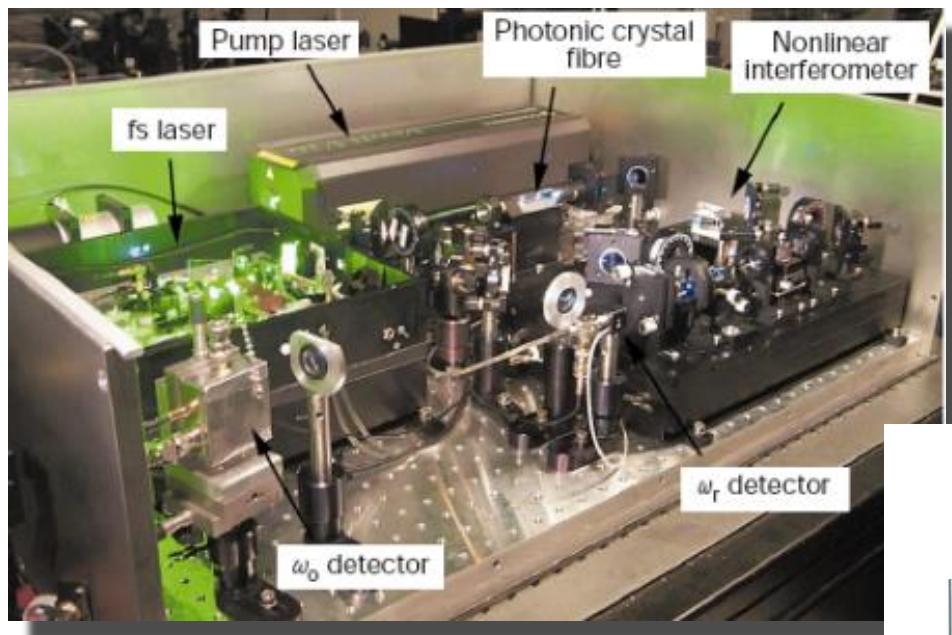


Nobel Prize Physics 2005:

*"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*



Theodor Hänsch John Hall



Комб-генератор –  
коммерчески  
доступное устройство

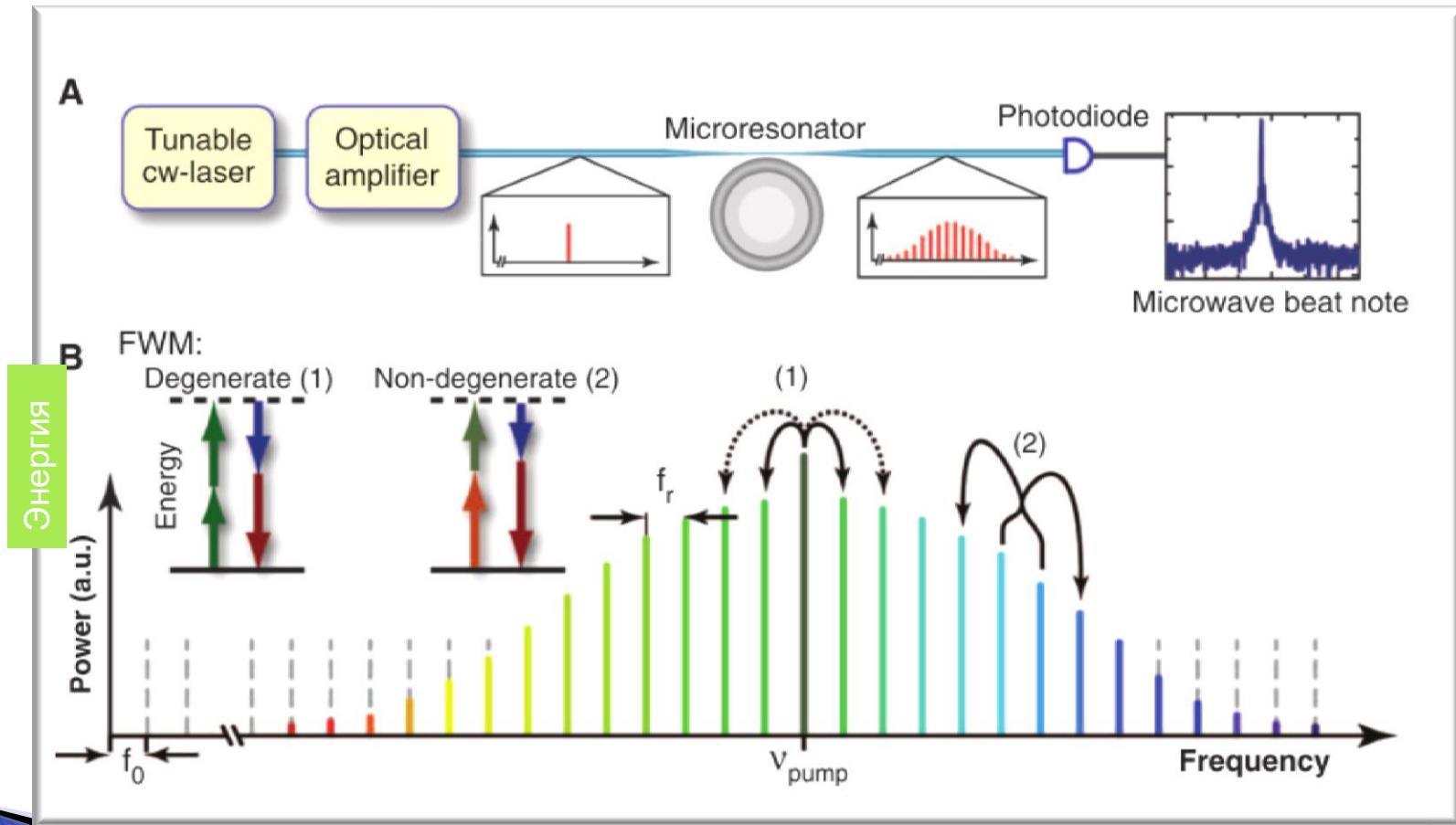


# Генерация оптических гребенок в микрорезонаторах

Порог для нелинейного  
преобразования:

$$P_{thresh} \propto V_m/Q^2$$

При  $Q > 10^9$  достаточно мВт на входе!

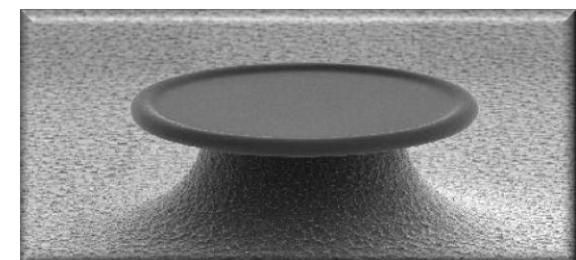




# Комб-генератор на микрорезонаторе – малые размеры, стоимость, потребляемая мощность...



>10000 раз  
меньше!



Диаметр: ~100  $\mu\text{m}$

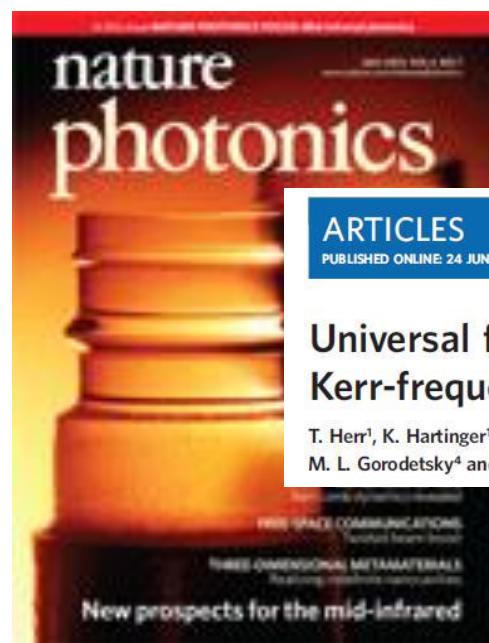
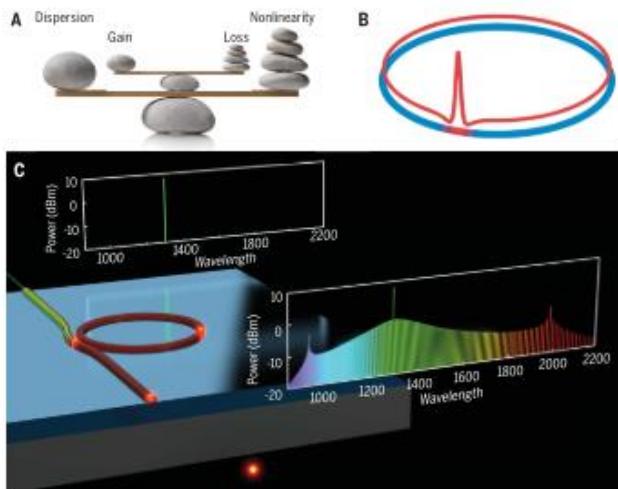
Проблема – фазовые шумы!



# Когерентные оптические гребенки и солитоны



Профессор  
Михаил Городецкий  
1966 – 2019



The equations that need to be solved are the following:

$$\frac{\partial L}{\partial \eta_1} - \frac{d}{dt} \frac{\partial L}{\partial \dot{\eta}_1} = \int \left( \mathcal{R} \frac{\partial \Psi^*}{\partial \eta_1} + \mathcal{R}^* \frac{\partial \Psi}{\partial \eta_1} \right) d\theta,$$



## Universal formation dynamics and noise of Kerr-frequency combs in microresonators

T. Herr<sup>1</sup>, K. Hartinger<sup>1,2</sup>, J. Riemensberger<sup>1</sup>, C. Y. Wang<sup>1,3</sup>, E. Gavartin<sup>1</sup>, R. Holzwarth<sup>2,3</sup>, M. L. Gorodetsky<sup>4</sup> and T. J. Kippenberg<sup>1,3\*</sup>

$$B = \sqrt{2\eta_0}, \quad (1.32)$$

$$\cos \varphi_0 = \frac{2B}{\pi f} = \frac{\sqrt{2\eta_0}}{\pi f}, \quad (1.33)$$

$$\zeta_0^{\text{max}} = \frac{\pi^2 f^2}{8}. \quad (1.34)$$

An approximate single soliton solution which accounts for a flat CW background is then given by

$$\Psi = \Psi_0 + \Psi_1 \approx \Psi_0 + Be^{i\varphi_0} \text{snoch}(B\theta), \quad (1.35)$$

The constant CW background  $\Psi_0$  may be found by inserting  $\Psi_0$  into eq. (1.24) as the lower branch [31] of the solution of



RESEARCH

REVIEW

OPTICS

## Dissipative Kerr solitons in optical microresonators

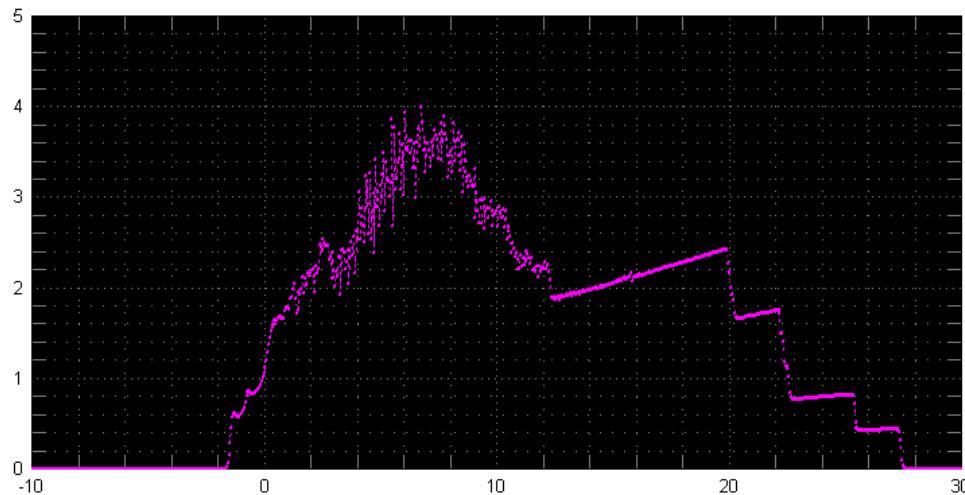
Tobias J. Kippenberg<sup>1\*</sup>, Alexander L. Gaeta<sup>2</sup>, Michal Lipson<sup>3</sup>, Michael L. Gorodetsky<sup>4,5\*</sup>

The development of compact, chip-scale optical frequency comb sources (microcombs) based on parametric frequency conversion in microresonators has seen applications in terabit optical coherent communications, atomic clocks, ultrafast distance

Science 361, 567 (2018)



# Теория и эксперимент



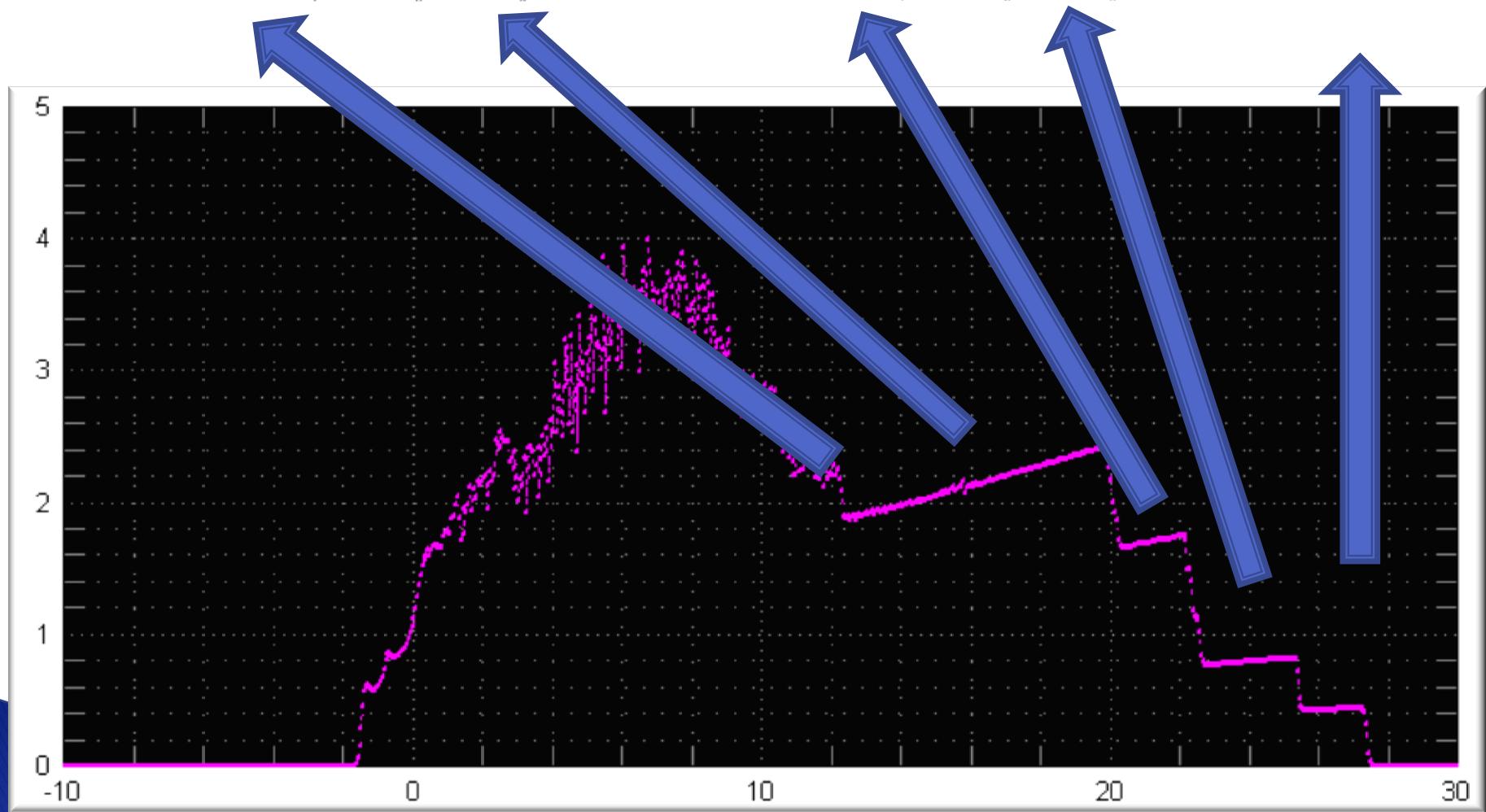
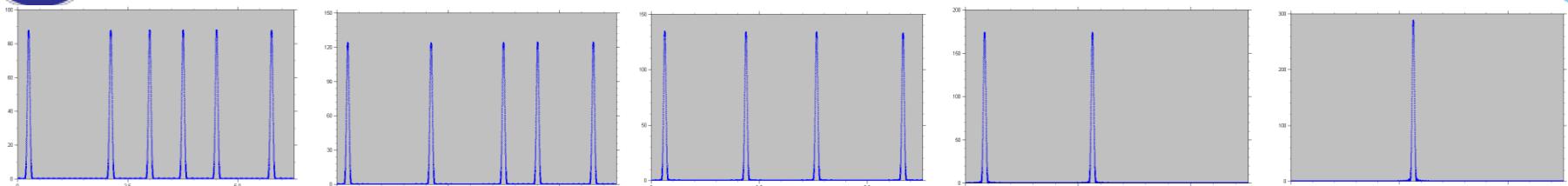
Численное  
моделирование



Эксперимент



# Ступеньки и солитоны



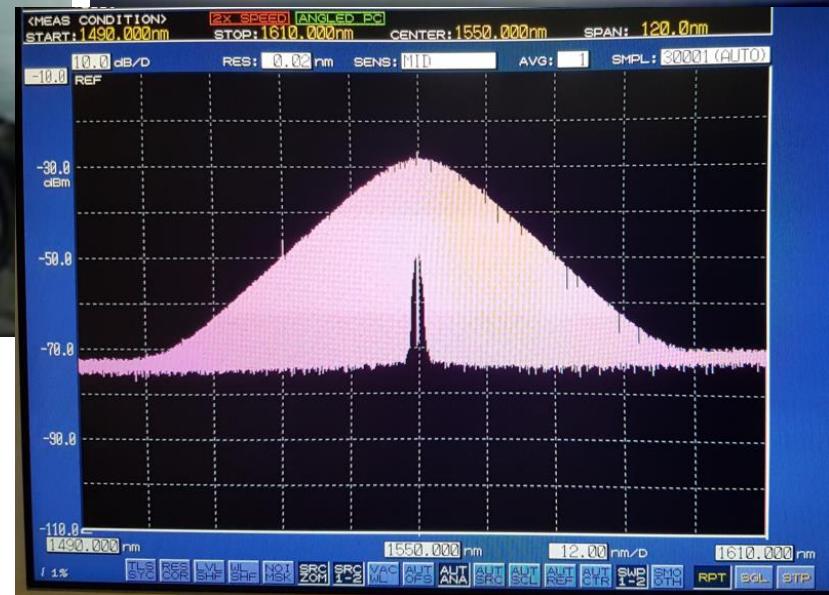


# Направления исследований лаборатории когерентной микрооптики и радиофотоники

- Исследование нелинейной динамики микрорезонаторов и лазеров.  
Генерация солитонов, платиконов,  
дисперсионные волны, солитонные кристаллы...
- Исследование новых материалов и технологий изготовления высокодобротных микрорезонаторов
- Разработка устройств на микрорезонаторах: узкополосные лазеры, модуляторы, источники гребенок, генераторы неклассических состояний света.
- Микрорезонаторы и метрология: вторичные стандарты частоты



# Изготовление кристаллических резонаторов



Reproducible  $Q$ -factors at the level of  
 $>10^9$  and submicron precision of  
geometry



# Ultra-high Q WGM – Self injection locking



## Narrow line requires:

1. Sophisticated frequency locking electronics  
(usually requires modulation – demodulation)
2. Narrow line single frequency pump laser  
(usually low power, requires additional bulky expensive EDFA to amplify)



# Ultra-high Q WGM – Self injection locking



## Narrow line requires:

1. Sophisticated frequency locking electronics  
(usually requires modulation – demodulation)
2. Narrow line single frequency pump laser  
(usually low power, requires additional bulky expensive EDFA to amplify)

Way to avoid the 1. : Rayleigh backscattering and self-injection locking

Quantum Electronics 26(8) 657–658 (1996)

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LETTERS TO THE EDITOR

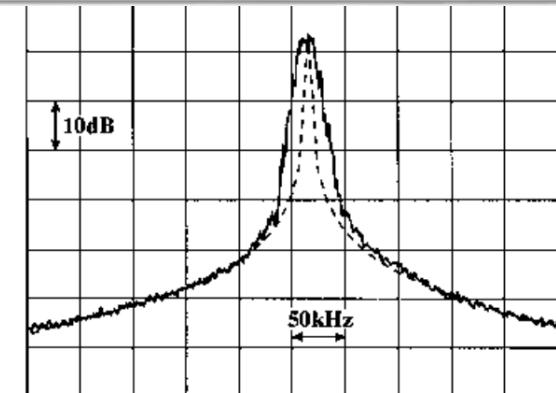
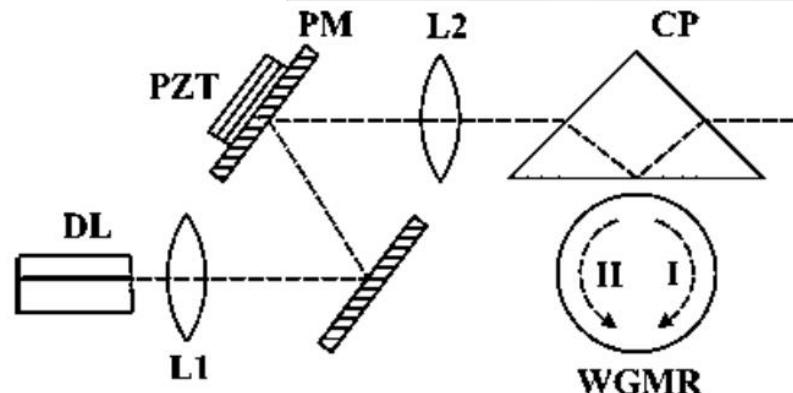
### High-coherence diode laser with optical feedback via a microcavity with ‘whispering gallery’ modes

V V Vasil'ev, V L Velichanski $\ddot{\text{i}}$ , M L Gorodetskii, V S Il'chenko,  
L Hollberg, A V Yarovitski $\ddot{\text{i}}$

Optics Communications 158 (1998) 305–312

### Narrow-line-width diode laser with a high- $Q$ microsphere resonator

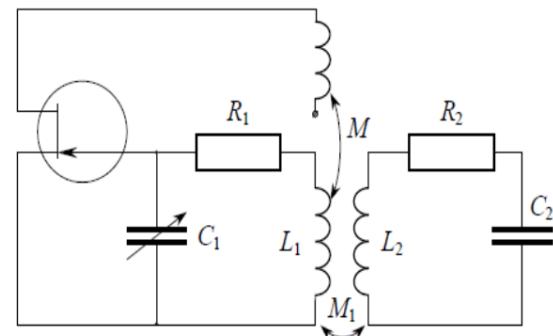
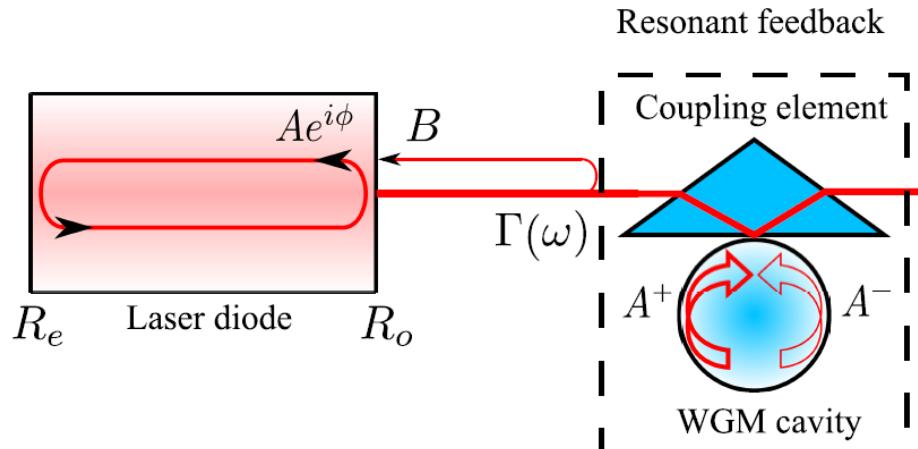
V.V. Vassiliev <sup>a,\*</sup>, V.L. Velichansky <sup>a</sup>, V.S. Ilchenko <sup>b</sup>, M.L. Gorodetsky <sup>b</sup>,  
L. Hollberg <sup>c</sup>, A.V. Yarovitsky <sup>a</sup>



M. L. Gorodetsky, A. D. Pryamikov, and V. S. Ilchenko,  
JOSA B17, 1051 (2000).



# Self-injection locking theory



$$A(t)e^{i\phi(t)} = iT_o B(t) + R_e R_o A(t - \tau_d) e^{i\omega\tau_d + 2(\gamma - \alpha)L + i\phi(t - \tau_d)},$$

$$B(t) = \frac{iT_o \Gamma(\omega)}{R_o} A(t - \tau_s) e^{i\omega\tau_s + i\phi(t - \tau_s)},$$

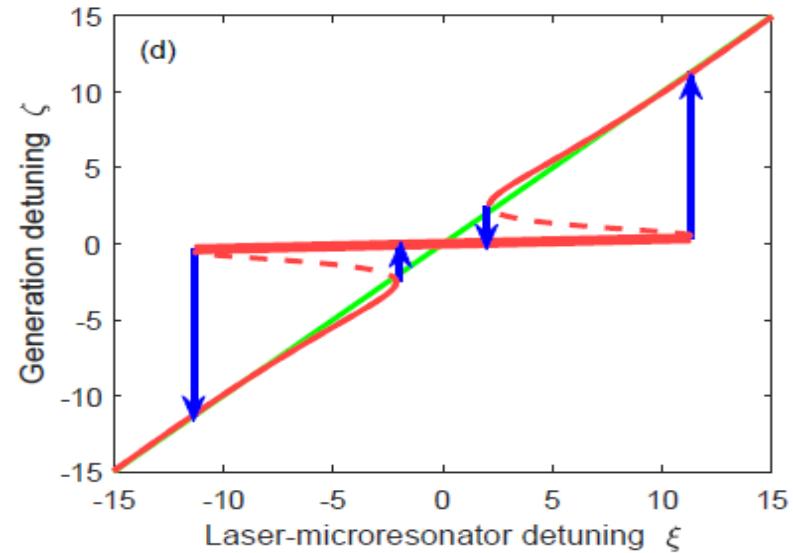
Analogous to Lang-Kobayashi equations,  
*Journ. Quant. El.* 16, 347 (1980)

**Stationary solution:**

$$\xi = \zeta + \frac{K}{2} \frac{2\zeta \cos \bar{\psi} + (1 + \beta^2 - \zeta^2) \sin \bar{\psi}}{(1 + \beta^2 - \zeta^2)^2 + 4\zeta^2}.$$

$$\xi = 2(\bar{\omega}_d - \omega_m)/\kappa_m$$

$$\zeta = 2(\omega - \omega_m)/\kappa_m$$





# Ultra-high Q WGM – some problems



## Narrow line requires:

1. Sophisticated frequency locking electronics  
(usually requires modulation – demodulation)
2. Narrow line single frequency pump laser  
(usually low power, requires additional bulky expensive EDFA to amplify)  
- Is it still important?

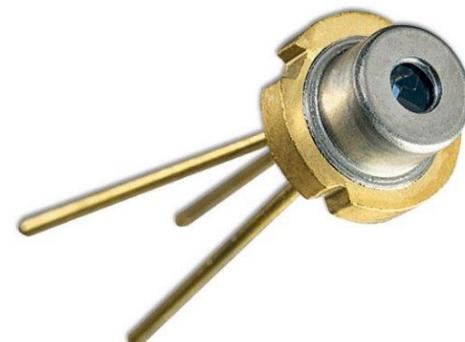


# Self injection locking with a multifrequency diode



## Narrow line requires:

1. Sophisticated frequency locking electronics  
(usually requires modulation – demodulation)
  2. Narrow line single frequency pump laser  
(usually low power, requires additional bulky expensive EDFA to amplify)
- **Way to avoid the 1 AND 2.** : lock a cheap multifrequency diode!



### NKT Koheras Boostik:

- Single frequency, tunable
- 1 kHz linewidth
- $\geq 100$  mW
- \$ 30k

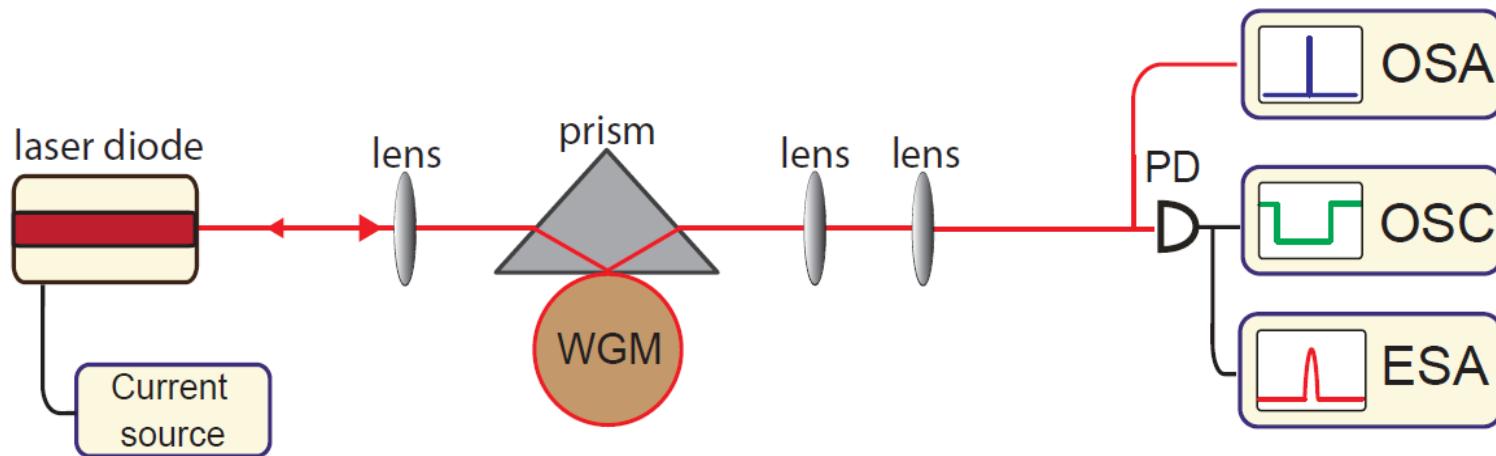
### A semiconductor laser diode:

- Multifrequency
- $\geq 10$  nm linewidth
- $\geq 100$  mW
- \$ 30

**can produce singe frequency, narrow line generation when self-injection locked.**



# Self-injection locking with a multifrequency diode

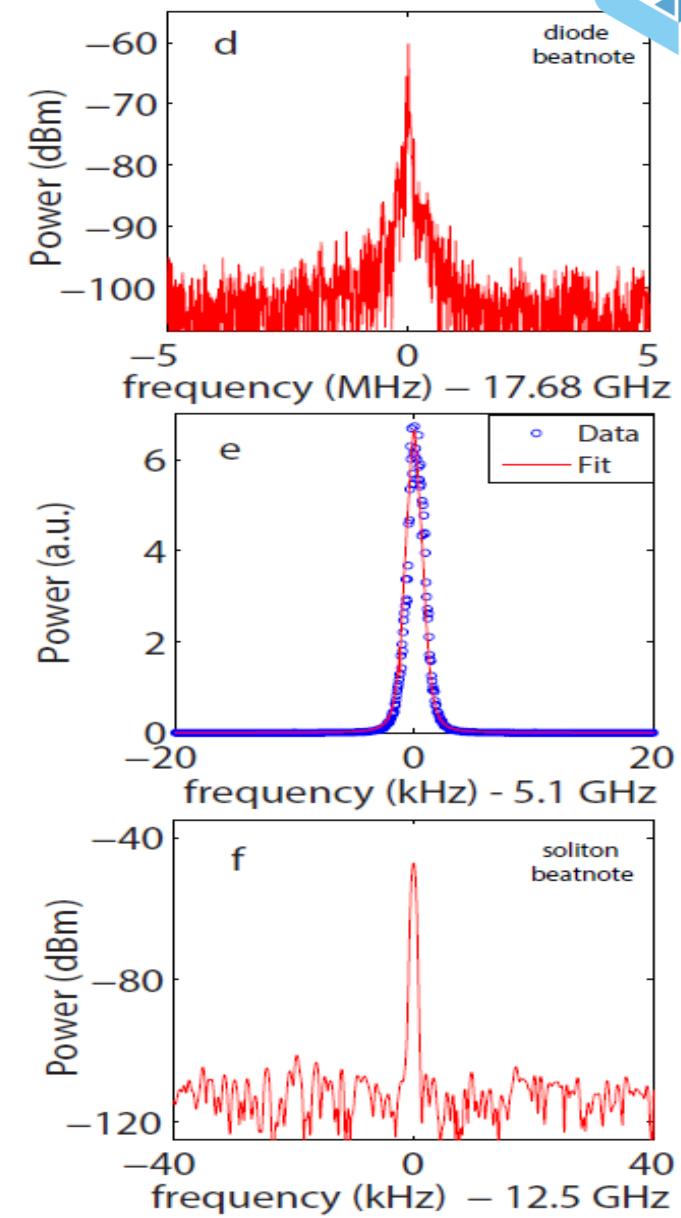
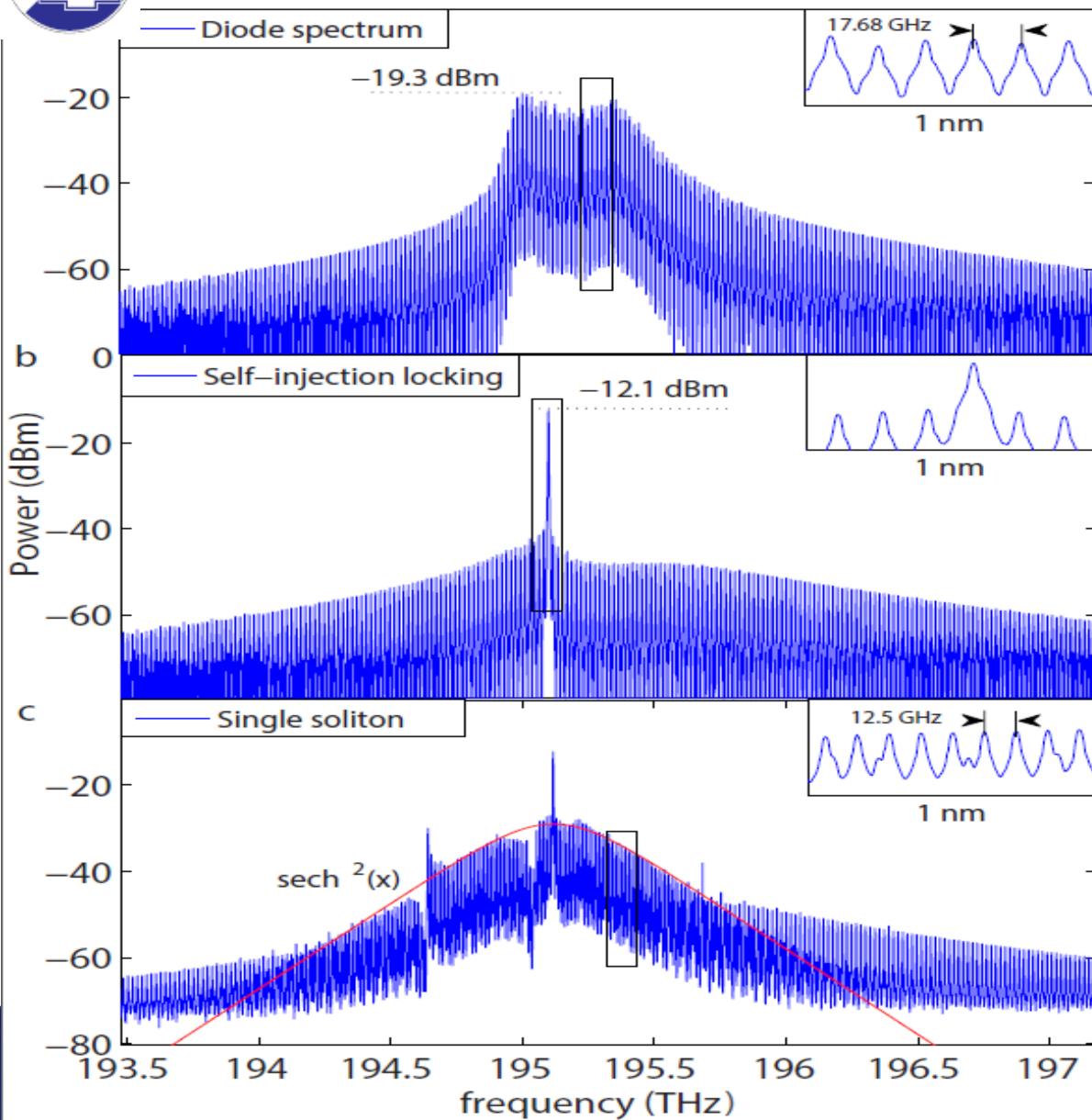


Diode: InP,  $\lambda=1535$  nm, spectrum width 10 nm (~50 lines),  $\Delta f \approx 17.6$  GHz,  $P = 200$  mW max

Microresonator: MgF<sub>2</sub>,  $Q \cong 10^9$ , FSR = 12.5 GHz



# Генерация узкой линией и генерация солитона





# Multimode laser and resonator interaction in depth



The standard multimode laser model:

$$\begin{aligned}\dot{N} &= \frac{I}{e} - \frac{N}{\tau_s} - \sum_l G_l^{(1)} S_l, \\ \dot{S}_l &= (G_l - G_{th}) S_l + N F_l,\end{aligned}$$

For the gain:

$$G_l = G_l^{(1)} - G_l^{(3)} S_l - \sum_{k \neq l} (G_{l(k)}^{(3)} + G_{l(k)}^{\text{Bogatov}}) S_k,$$

$$G_l^{(1)} = \theta(N - N_g - D(\lambda_l - \lambda_{peak})^2),$$

Bogatov model: variations of  $n$ , caused by the dynamic inhomogeneity of the electron density due to the stimulated emission of the excited electrons under the influence of mode interference creates a temporal phase lattice.

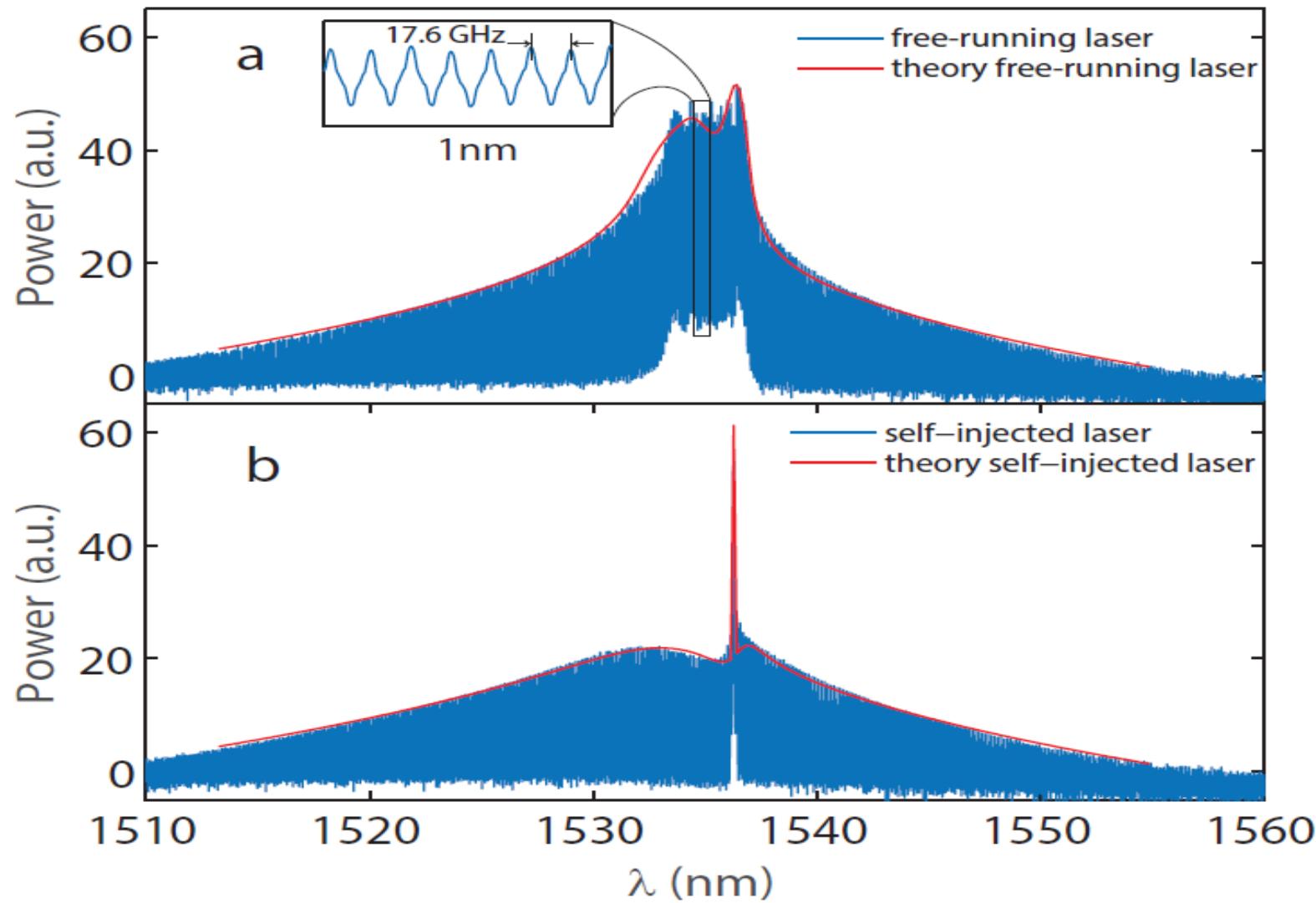
$$G_{l(k)}^{\text{Bogatov}} = \frac{3}{4} \theta^2 (N - N_g) \frac{\frac{1}{\tau_s} + \frac{3}{2} \theta S + \alpha \Omega_{l(k)}}{\left(\frac{1}{\tau_s} + \frac{3}{2} \theta S\right)^2 + \Omega_{l(k)}^2},$$

The numerical model based on the Bogatov model and Lang-Kobayashi equations was developed. To simplify the analysis, we assumed that each laser mode interacts efficiently with only one mode of the microresonator

*R. R. Galiev, N. G. Pavlov, N. M. Kondratiev et al.  
Optics Express, 26, 30509 (2018)*

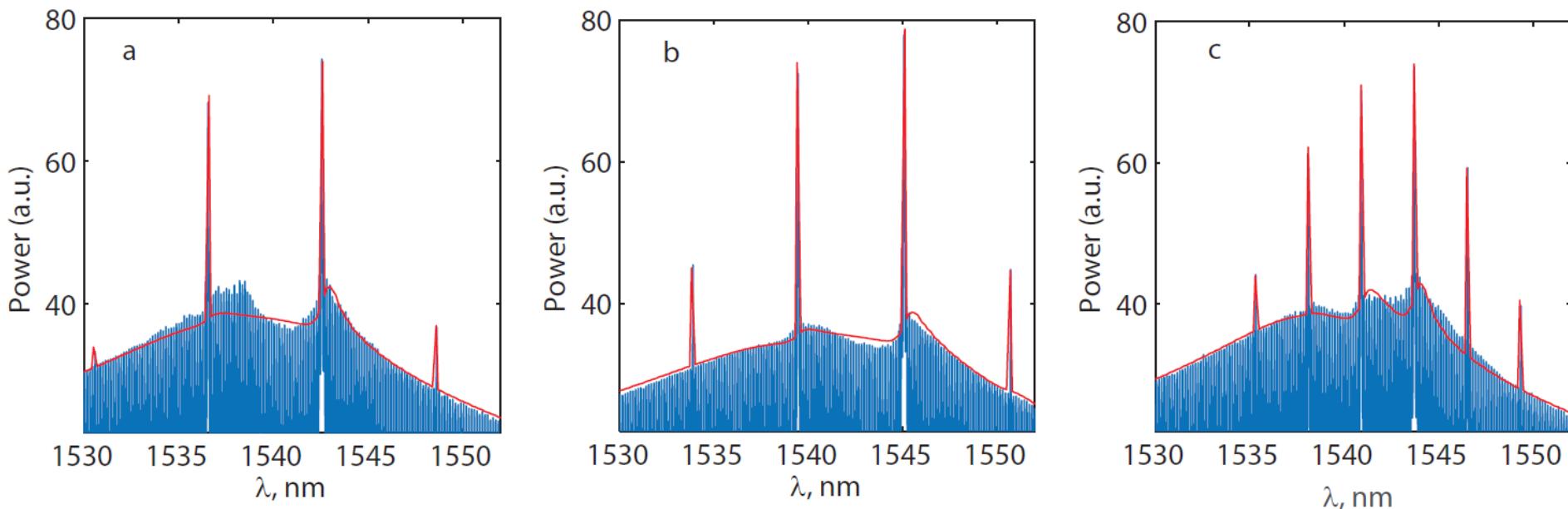


# Spectrum collapse and Bogatov effect





# Several-frequency radiation of the self-injection locked laser

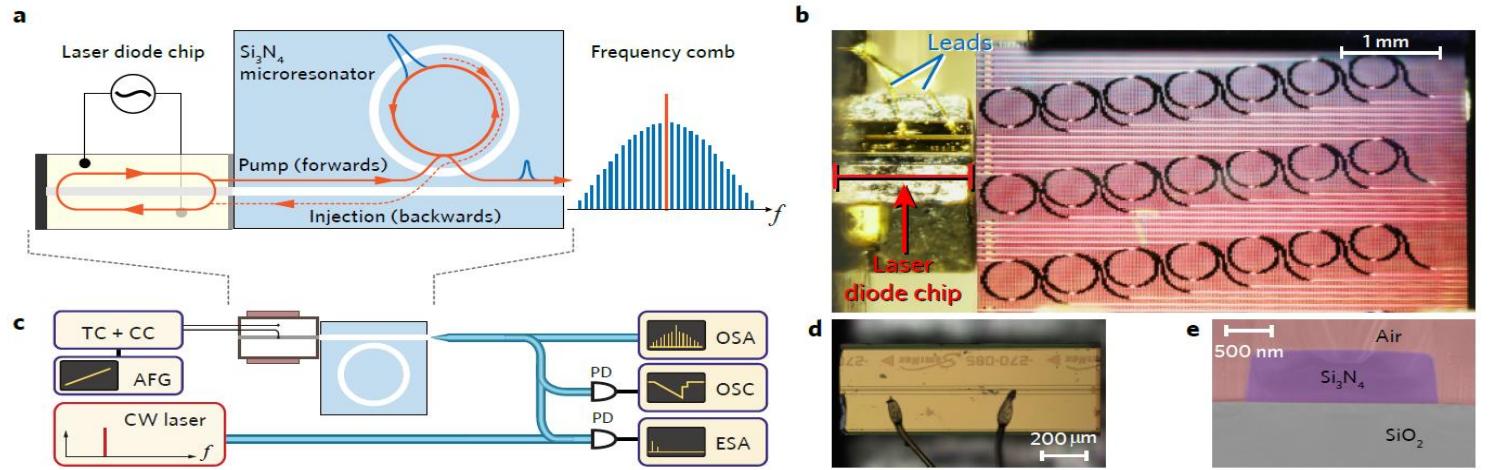


Optical spectrum of the several-frequency radiation of the self-injection locked laser  
blue – experiment, red – model

- Effect was observed on many different resonators
- Usually frequency interval between locked modes is a least common multiple of the FSRs
- Sometimes it isn't – locking to different family of modes? Need future investigation.



# Photonic integrated soliton microcomb

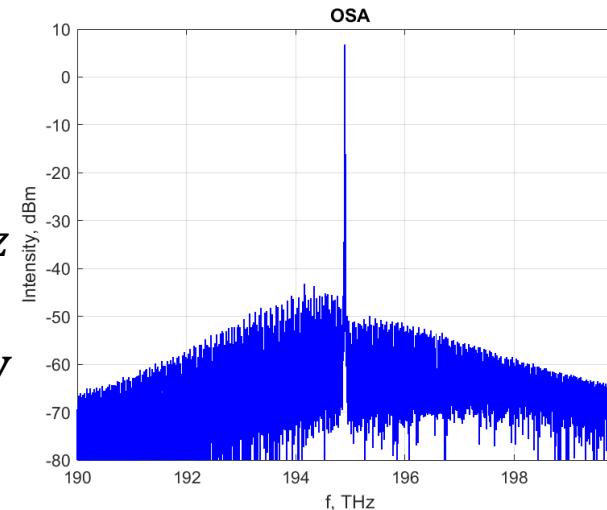


$$SiN : Q \cong 10^7$$

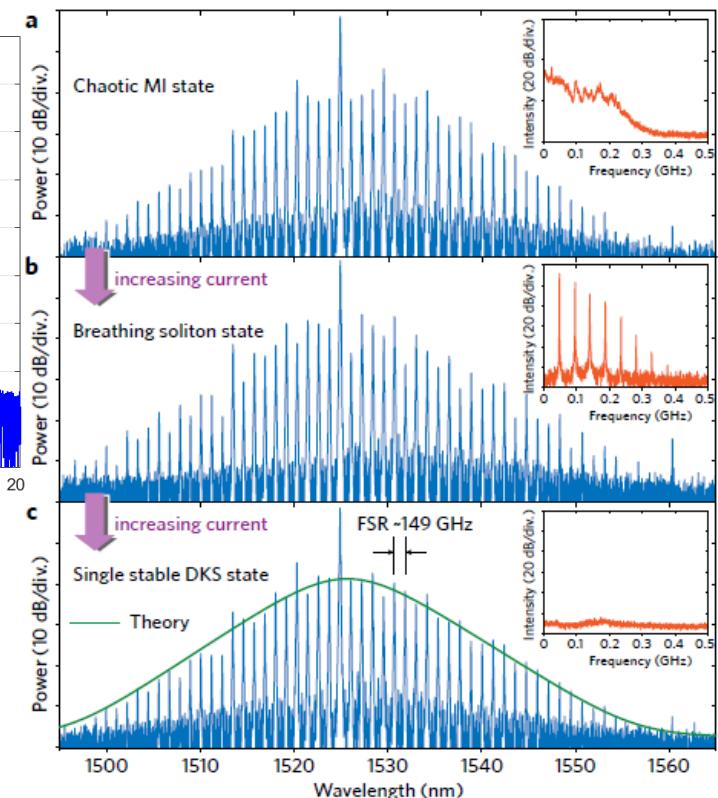
$$FSR < 100 \text{ GHz}$$

$$\Delta f: 2 \text{ MHz} \rightarrow 0.7 \text{ kHz}$$

$$W_{pump,min}^{DKS} \cong 50 \text{ mW}$$



A. S. Raja, A. S. Voloshin, H. Guo et.al.,  
arXiv:1810.03909 (2018)  
(accepted to Nature Communications)





# Добротность выше $10^9$ в кремниевых резонаторах



Letter

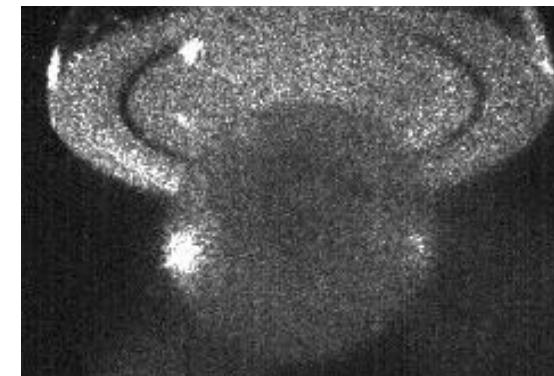
Vol. 5, No. 12 / December 2018 / Optica

1525

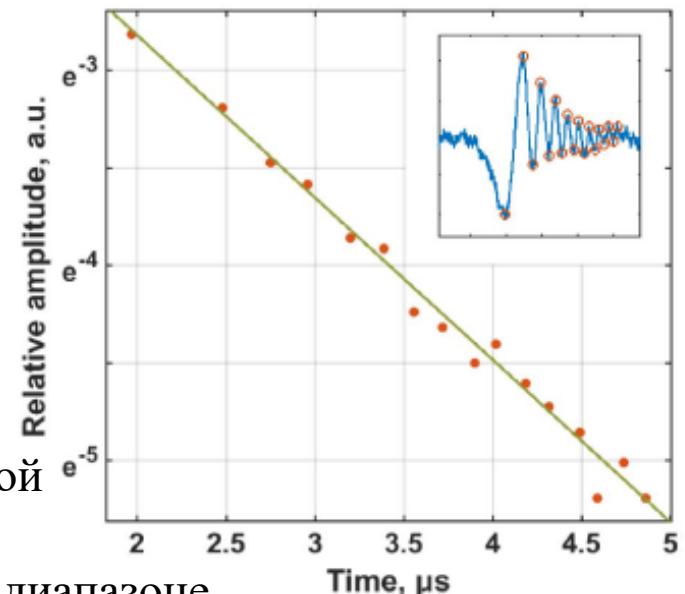
# optica

## Billion Q-factor in silicon WGM resonators

A. E. SHITIKOV,<sup>1,2</sup> I. A. BILENKO,<sup>1,2\*</sup> N. M. KONDRATIEV,<sup>2</sup> V. E. LOBANOV,<sup>2</sup> A. MARKOSYAN,<sup>3</sup> AND M. L. GORODETSKY<sup>1,2</sup>



- Совместимость с полупроводниковой интегральной технологией
- Малые потери в среднем ИК и ТГц диапазоне

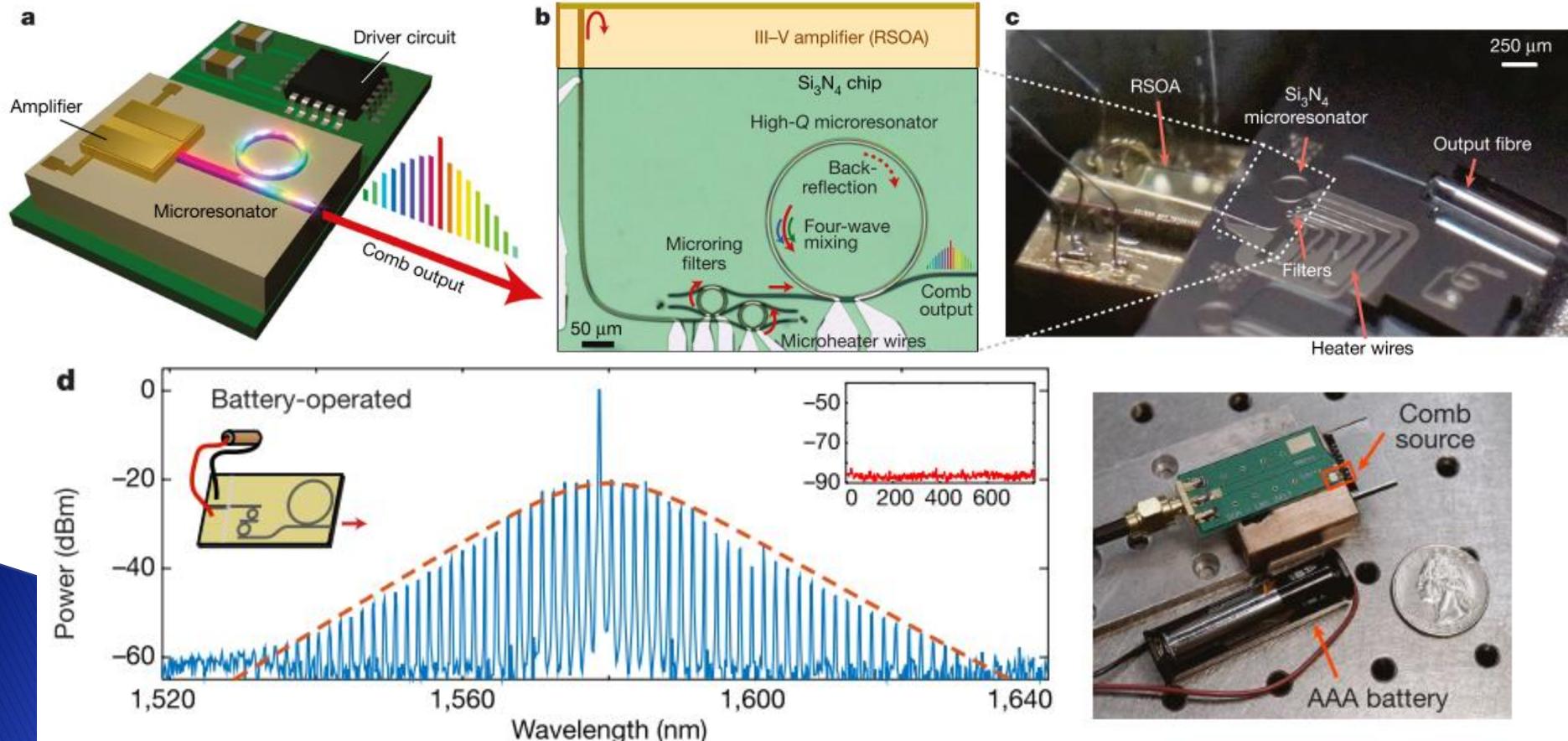




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## Battery-operated integrated frequency comb generator

Brian Stern<sup>1,2</sup>, Xingchen Ji<sup>1,2</sup>, Yoshitomo Okawachi<sup>3</sup>, Alexander L. Gaeta<sup>3</sup> & Michal Lipson<sup>2\*</sup>





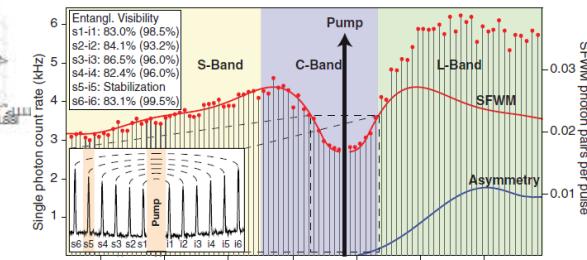
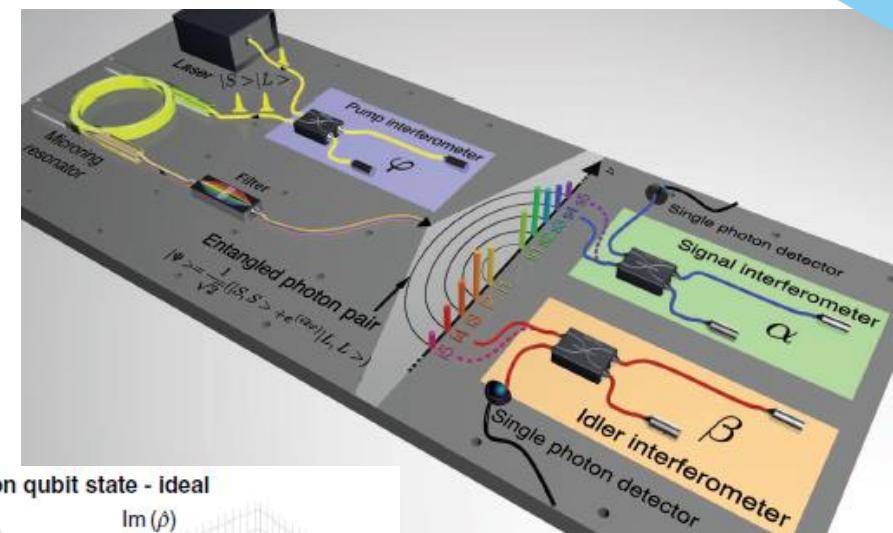
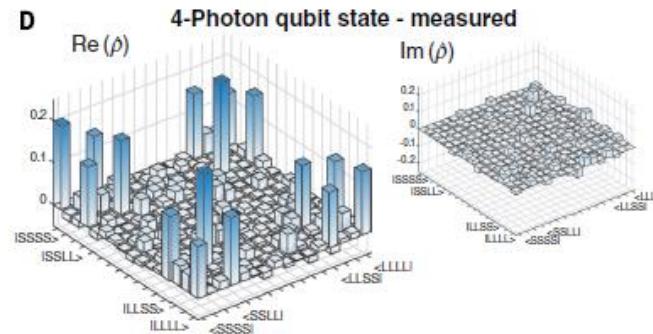
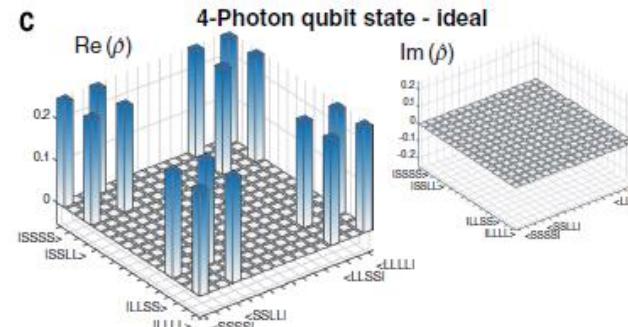
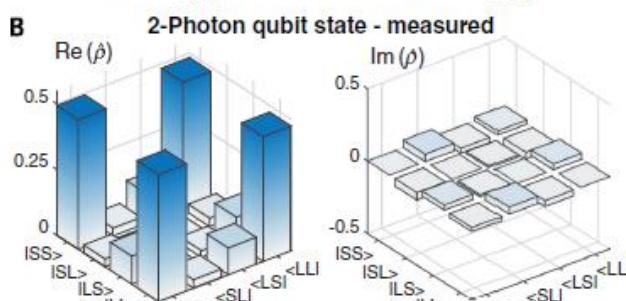
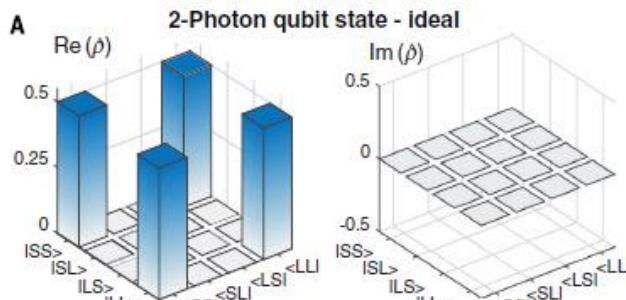
# Достижения в мире: генерация перепутанных состояний



## Generation of multiphoton entangled quantum states by means of integrated frequency combs

Christian Reimer,<sup>1\*</sup> Michael Kues,<sup>1\*†</sup> Piotr Roztocki,<sup>1</sup> Benjamin Wetzel,<sup>1,2</sup>  
 Fabio Grazioso,<sup>1</sup> Brent E. Little,<sup>3</sup> Sai T. Chu,<sup>4</sup> Tudor Johnston,<sup>1</sup> Yaron Bromberg,<sup>5,‡</sup>  
 Lucia Caspani,<sup>6,§</sup> David J. Moss,<sup>7||</sup> Roberto Morandotti<sup>1,8,†</sup>

Science v.351 2016



$$Q=2 \times 10^5$$

$$\text{FSR} = 200 \text{ GHz}$$

$$T_{\text{pulse}} = 570 \text{ ps}$$

$$\text{Rate} = 16.8 \text{ MHz}$$

$$\text{Loss} = 14 \text{ dB}$$



# Достижения в мире: генерация перепутанных состояний



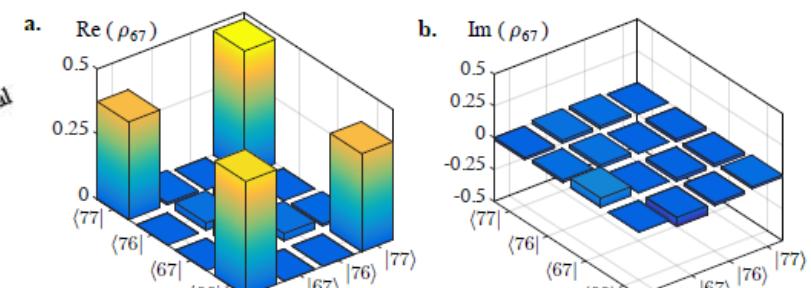
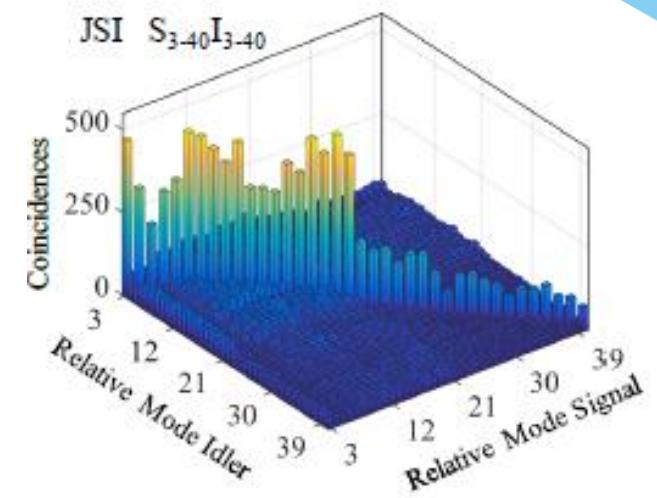
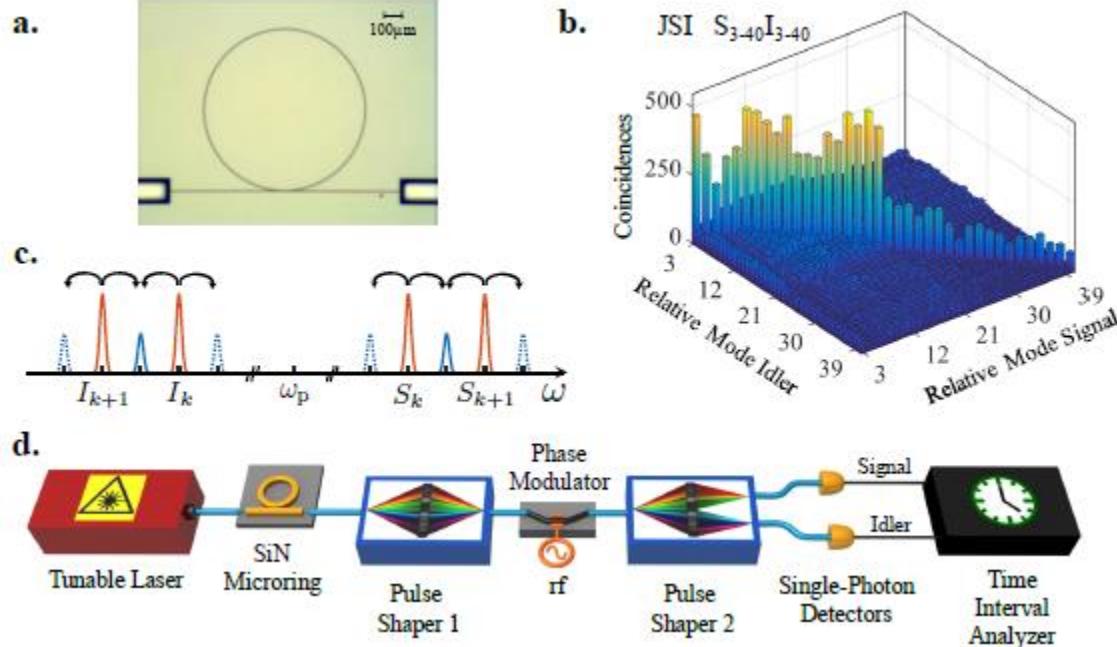
Research Article

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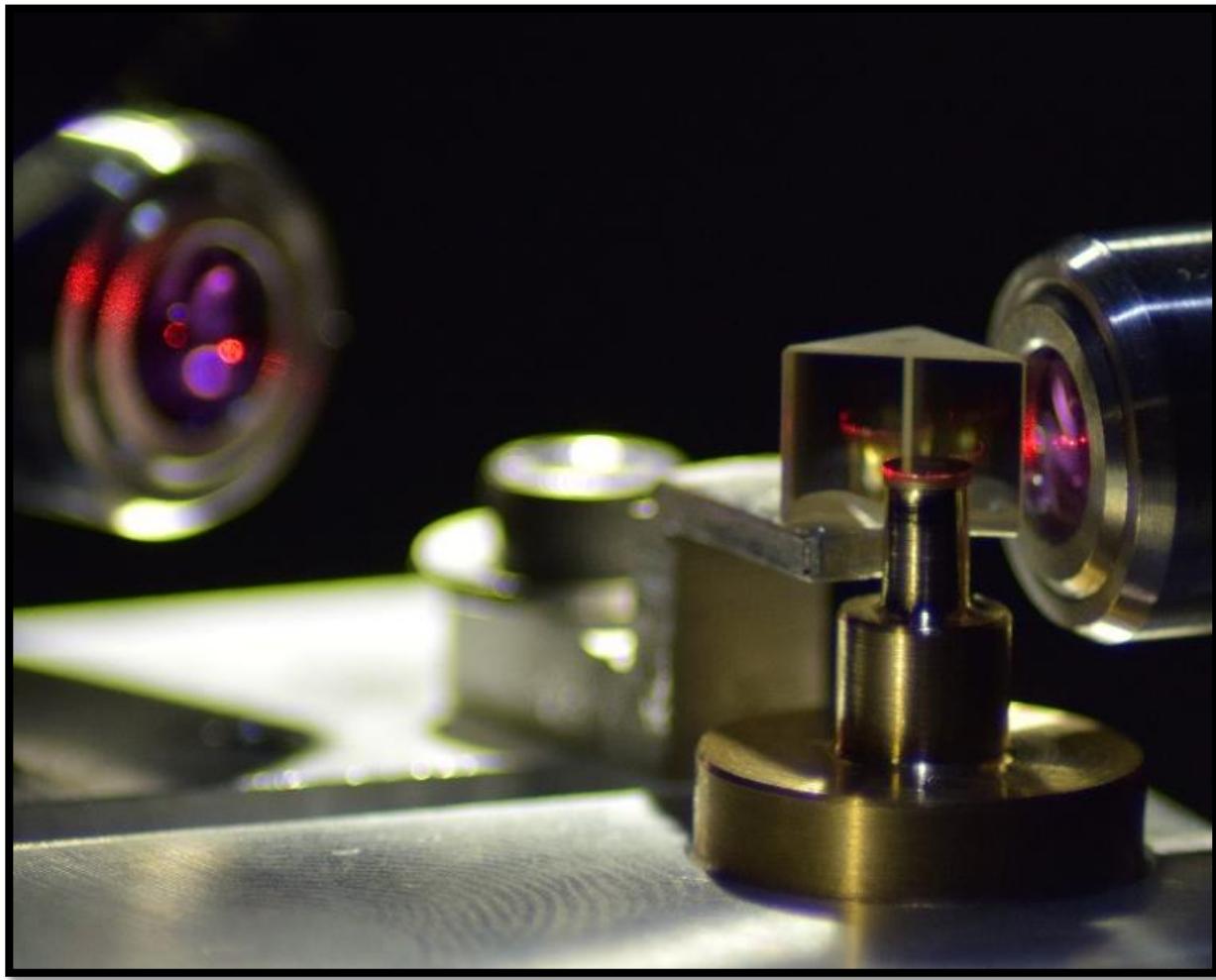
Optics EXPRESS

## 50-GHz-spaced comb of high-dimensional frequency-bin entangled photons from an on-chip silicon nitride microresonator

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Кубиты и кутриты на  
гребенке их 40 пар мод



*Спасибо за внимание!*