Tunable single-frequency lasing in whispering gallery resonators

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ABSTRACT

Whispering gallery resonators (WGRs) are ideally suited for the realization of miniaturized lasers. Due to their high quality factor and small mode volume, they allow for low-threshold and narrow-linewidth emission from (sub)millimeter-sized cavities made of laser-active materials. However, so far the majority of experimental realizations relies on expensive pump light sources like narrow-linewidth or pulsed laser systems, impeding most applications. We demonstrate two whispering-gallery-based single-frequency lasers pumped by compact spectrally multimode low-cost laser diodes. The spheroidally-shaped millemeter-sized WGRs are made of Pr:LiLuF_4 and Nd:YVO_4. They provide quality factors beyond 10^7 at the lasing wavelengths (640 nm and 1064 nm, respectively). The pump light is focused onto the rim of the WGR. We observe single frequency emission at milliwatt output powers. The temporal stability of the output power and of the output frequency are determined to be ±1.5 % and ±30 MHz within 30 min, respectively. By changing the temperature of the cavity, we achieve mode-hop-free tuning exceeding 11 GHz.

Keywords: Whispering gallery modes, Lasing

1. INTRODUCTION

Whispering gallery resonators (WGRs) are an outstanding platform for microphotonic lasers due to their high quality factor (Q-factor) and small mode volume, which allow for low-threshold and narrow-linewidth lasing in laser-actice WGRs.[1] Also passive WGRs can be used for frequency stabilization of external lasers.[2,3] Since the first demonstration of lasing in laser-active WGRs,[4] laser oscillation in such cavities has been demonstrated in a large variety of materials like liquid droplets,[5,6] polymers,[7,8] glasses,[9,10] wide bandgap crystals,[11,12] and semiconductors.[13,14] Typically, whispering-gallery-based lasers are resonantly pumped with a narrow-linewidth laser source, whose light is coupled into whispering gallery modes. Thus, controlled evanescent coupling, e.g. with a tapered fiber or with a coupling prism is required. Non-resonant excitation using nanosecond-long laser pulses is also employed. However, this does not allow for stable continuous-wave laser operation. Since both excitation schemes require expensive light sources, they are inappropriate for applications outside of scientific research laboratories.

In order to overcome this severe drawback, different excitation alternatives were presented in the past. Among those are: resonant pumping by means of a low-cost laser diode enabled by lowering the Q-factor at the excitation wavelength,[9,15] resonant pumping with a broadband amplified spontaneous emission (ASE) light source,[16] and non-resonant pumping using a light-emitting diode (LED).[17] Besides the costs and complexity of the excitation light sources, another limiting factor for the applicability of whispering-gallery-based micro-lasers is their typically poor laser performance, concerning the high number of oscillating modes, poor directionality of the laser emission, unsatisfying temporal power and frequency stability, low output power and rather limited spectral tunability. In the case of a dye-based gain medium, bleaching puts a limit for the long-term usability of the laser. In the past,

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several approaches have been presented which solve some of the above mentioned issues,[1,18–20] while neglecting other insufficiencies.

Here, we present an approach which addresses all of the above mentioned points, while simultaneously avoiding the requirement for an expensive pump light source. We use low-cost laser diodes for non-resonant pumping of four-level laser-active microresonators. The spatially selective excitation enables single-frequency lasing. By changing the temperature of the WGR, modehop-free tuning of the emission frequency is achieved.

2. ESTIMATION OF LASER THRESHOLD AND EXCITATION EFFICIENCY

We assume a spheroidally shaped whispering gallery resonator with the major radius R made of a four-level laser-active material, i.e. its quality factor Q_l at the lasing wavelength λ_l is high even without being pumped. The pump light at λ_p is focused into the equatorial area of the resonator rim from the side (see Fig. 1). The cross section of the lasing whispering gallery mode can be estimated by the product of its width w_m and its height h_m. For a millimeter-sized resonator, we have typically $w_\mathrm{m} = 5$ µm and $h_\mathrm{m} = 15$ µm.[21] The laser radiation is coupled out via a prism. The pump threshold for this configuration can be estimated by[17]

$$P_\mathrm{th} = \frac{2\pi n_\mathrm{l} h c_0 V_\mathrm{m}}{\lambda_\mathrm{l}\lambda_\mathrm{p} Q_\mathrm{l} \sigma_\mathrm{em} \tau \eta} \tag{1}$$

with the refractive index n_l of the resonator material at the lasing wavelength, Planck's constant h, vacuum speed of light c_0, mode volume $V_\mathrm{m} \approx 2\pi R w_\mathrm{m} h_\mathrm{m}$, emission cross section σ_em, fluorescence lifetime τ and excitation efficiency η. The latter quantifies how much excitation light is absorbed in the mode volume of the whispering gallery mode. It can be estimated by $\eta \approx T[1 - \exp(-\alpha w_\mathrm{m})] \approx T\alpha w_\mathrm{m}$, with the transmission T of the air-crystal surface and the absorption coefficient α of the resonator material at the pump wavelength. It should be mentioned that spatial hole burning due to the standing-wave pattern formed by the counterpropagating lasing fields in the resonator is neglected in the estimation. This is only valid for low pump powers at which no gain saturation occurs. The latter can be included into this model via a reduced excitation efficiency. Here, we will investigate two different laser-active materials: praseodymium-doped lithium lutetium fluoride ($Pr{:}LiLuF_4$) and neodymium doped yttrium orthovanadate ($Nd{:}YVO_4$).

First, we consider a WGR ($R = 1.5$ mm) made of $Pr{:}LiLuF_4$. This material provides several dipole transitions in the visible spectral range.[22] With $\sigma = 2.2 \times 10^{-23}$ m^2, the ordinarily polarized emission line at $\lambda_\mathrm{l} = 640$ nm is the most prominent one.[23] Here, the lifetime $\tau = 38$ µs.[23] At the pump wavelength $\lambda_\mathrm{p} = 445$ nm we have $\alpha \approx 700$/m.[23] The refractive index of this material in the visible spectral range is about 1.5,[24] i.e. $T = 0.96$. We assume $V_\mathrm{m} = 7 \times 10^{-13}$ m^3 and $Q_\mathrm{l} = 10^7$. Using these parameters, in the abovementioned expressions, we can estimate the excitation efficiency $\eta \approx 0.3$ % and the oscillation threshold $P_\mathrm{th} \approx 170$ mW.

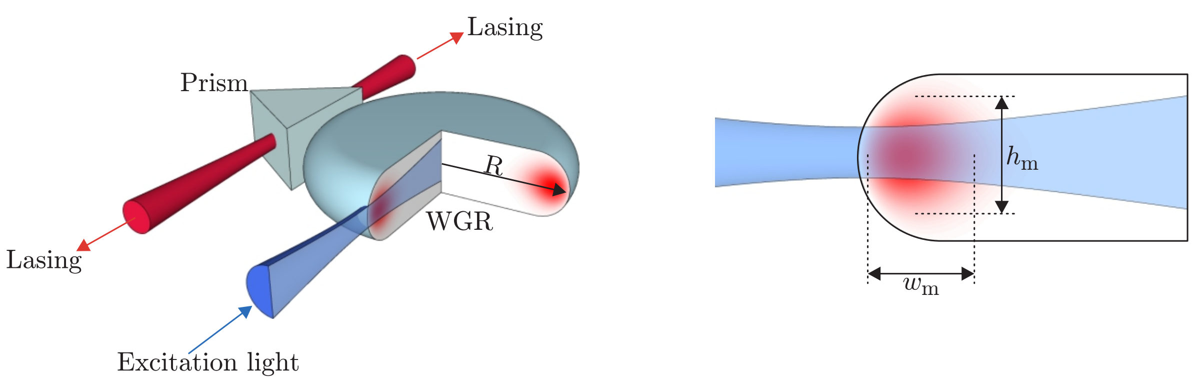

Figure 1. Scheme of a whispering-gallery based laser. The whispering gallery resonator with the major radius R is made of a laser active material and pumped with excitation light. The generated laser light is extracted by a prism. The cross section of the intracavity laser light can be estimated by the product $h_\mathrm{m} w_\mathrm{m}$.

For a resonator ($R = 0.4$ mm) made of Nd:YVO$_4$, we have the following values: $n_\mathrm{l} = 2.17$ for extraordinarily polarized light at $\lambda_\mathrm{l} = 1064$ nm,[25] $\sigma_\mathrm{em} = 12 \times 10^{-23}$ m^2,[25] $\tau = 50$ µs,[17] $Q_\mathrm{l} = 10^7$, $V_\mathrm{m} = 2 \times 10^{-13}$ m^3, $\lambda_\mathrm{p} = 810$ nm, $\alpha = 1000/$m[17] and $T = 0.89$. With these parameters, we get $\eta \approx 0.5$ % and $P_\mathrm{th} \approx 2$ mW. Thus, simple diode lasers should be sufficient to drive whispering-gallery based lasing applying both materials with the scheme sketched in Fig. 1.

3. EXPERIMENTAL SETUP

The whispering gallery resonators are fabricated by computer-controlled laser ablation and subsequent polishing with diamond slurry.[26] For the one made of Pr:LiLuF$_4$ ($R = 1.5$ mm), the quality factor for critical coupling is $Q_\mathrm{l} = 1.5 \times 10^7$ at the lasing wavelength. For the one made of Nd:YVO$_4$ ($R = 0.4$ mm), we achieve $Q_\mathrm{l} = 1 \times 10^7$. The experimental setups for the characterization of the lasing properties of both configurations are sketched in Fig. 2.

The praseodymium-doped resonator is pumped by a diode laser (LD-445-1000MG, Roithner Lasertechnik) with a maximum output power of 1 W at 455 nm wavelength. The pump light is focused onto the rim using two aspheric lenses. Here, the emitter's active area is imaged 1:1 onto the rim. A half-wave plate between the two lenses ensures extraordinary polarization of the pump light. The generated laser light at 640 nm wavelength is coupled out of the WGR using a prism made of SF11 glass.

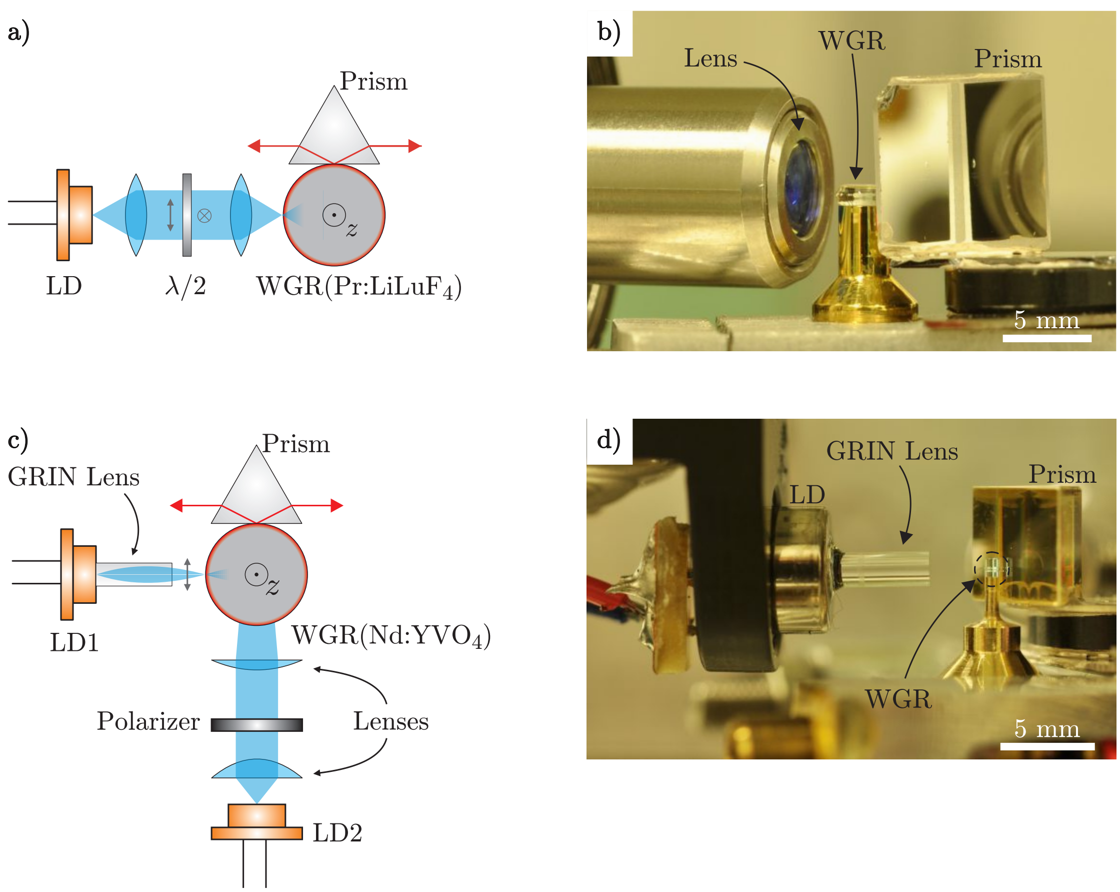

Figure 2. Sketches (a,c) and photographs (b,d) of the experimental setup for whispering-gallery-based lasing using WGRs made of Pr:LiLuF$_4$ and Nd:LiLuF$_4$. The latter is pumped by two laser diodes (LD1 and LD2). The first is to generate laser light, the second enables to heat the resonator and by this means to tune the emission wavelength. The polarization of the pump light is respectively denoted by $\otimes$ (extraordinary) and $\updownarrow$ (ordinary).

For the neodymium-doped resonator, we use two laser diodes. The first (RLT808-100G, Roithner Lasertechnik) emits at room temperature around 810 nm wavelength with up to 100 mW optical output power. The emitted spatially single-mode light is focused onto the rim of the WGR by means of a gradient-index (GRIN) lens, which is bonded directly onto the window of the laser diode. It serves to pump the stimulated emission process. The extent of the pump spot at the rim is smaller than 5 µm in z direction, thus it is smaller than the one of typical resonator modes. This justifies the scheme sketched in Fig. 1. Temperature changes of the WGR are induced by a second laser diode emitting around 810 nm wavelength, whose light is weakly focused onto the WGR crystal. In our experimental realization, a polarizer is used to adjust the optical power and with this the heating power. A rutile coupling prism extracts a fraction of the generated laser light. The output radiation of both configuration is characterized with a powermeter, a scanning Fabry-Pérot interferometer to prove single-frequency emission and a camera to analyze the transverse intensity distribution.

4. RESULTS

4.1 WGR made of praseodymium-doped lithium lutetium fluoride

At 220 mW excitation power, laser oscillation at 640 nm wavelength starts. Increasing the excitation power to 800 mW, the power of the ordinarily polarized laser light coupled out by the prism grows up to 1.2 mW in each of the two output directions. The lasing threshold strongly depends on the position of the focal spot with respect to the equatorial plane of the resonator. If it is displaced by only 10 µm in polar direction, the oscillation threshold exceeds the maximum pump power available.

Measuring the transmission of the laser light through a scanning Fabry-Pérot interferometer confirms single frequency operation of the whispering-gallery-based laser (Fig. 3a). We observe a Gaussian transverse intensity distribution of the laser light if the focal spot of the excitation light is in the equatorial plane (Fig. 3b). A displacement in polar direction leads to an emission pattern with two lobes (Fig 3c). Determining the beam diameter in x and z direction as a function of the position y for the Gaussian intensity pattern, we determined the beam quality to $M_x^2 = 1.3$ and $M_z^2 = 1.5$ (Fig. 3d). The measurement shows different focal spots for the beam in x and in z direction, i.e. a slight astigmatism.

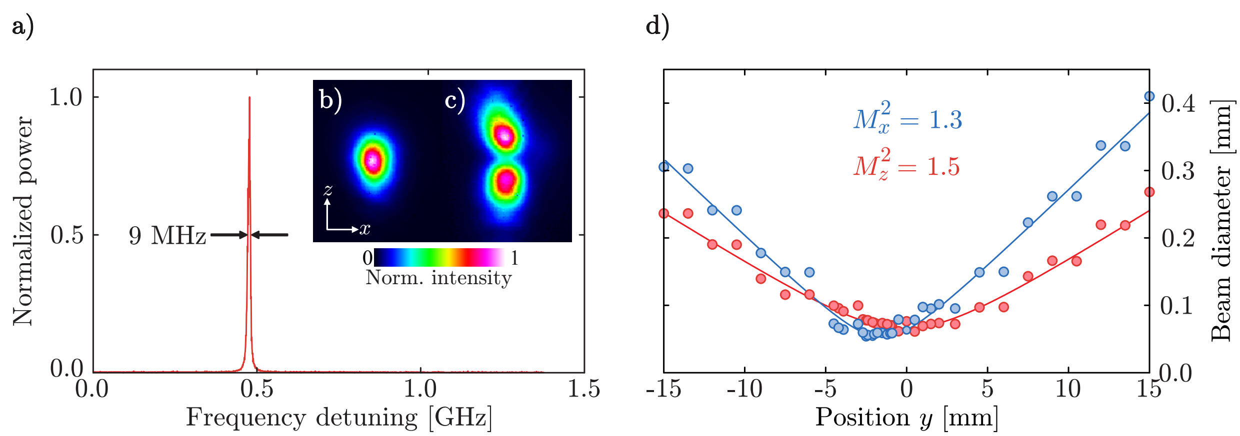

Figure 3. Transmission of the laser light generated in the whispering gallery resonator through a scanning Fabry Pérot interferometer with 1.5 GHz free spectral range (a). Transverse intensity patterns of the generated laser light at 640 nm wavelength for excitation in the equatorial plane (b) and for excitation displaced in polar direction (c). Beam diameters in x and z directions as a function of the position y (d). From these data, $M_x^2 = 1.3$ and $M_z^2 = 1.5$ are determined.

4.2 WGR made of neodymium-doped yttrium orthovanadate

Similar to the configuration with the WGR made of $Pr:LiLuF_4$, we have characterized the laser emission from a WGR made of $Nd:YVO_4$ with respect to oscillation threshold, single-frequency emission and transverse intensity distribution.[27] Qualitatively, the observations coincide with the ones described above. The minimum oscillation threshold here is 5 mW. It also strongly depends in the position of the focal spot with respect to the equatorial plane. At 100 mW excitation power, the power at 1064 nm wavelength grows up to 1.4 mW in each of the two outputs with ±1.5 % temporal stability during 30 min operation.

Single-frequency operation is again confirmed by measuring the transmission of the laser light through a scanning Fabry-Pérot interferometer (Fig. 4a). The temporal frequency stability is ±30 MHz during 30 min operation. Also here, we observe a Gaussian emission pattern by exciting the laser emission in the equatorial plane (Fig. 4b). The beam quality is determined to be $M_x^2 = 2.1$ and $M_z^2 = 1.9$ in this state. A two-lobe intensity pattern appears when the focal spot is displaced in polar direction.

We also quantify the spectral tunability of the system.[27] While changing the optical heating power by rotating the polarizer between laser diode and WGR (Fig. 2c), the transmission of the scanning FPI is recorded. From the shift of the peaks in the FPI transmission signal we deduce the frequency shift of the emission frequency of the WGR-laser. Figure 4c illustrates the corresponding measurement data, proofing about 11 GHz of mode-hop free tuning. The experimentally determined tuning rate is about 0.15 GHz/mW. Around 75 mW of optical heating power the laser process becomes dual-mode. The frequency difference between these two modes is of the order of the FSR of the WGR (inset of Fig. 4c), which is about 55 GHz (≈ 0.2 nm).

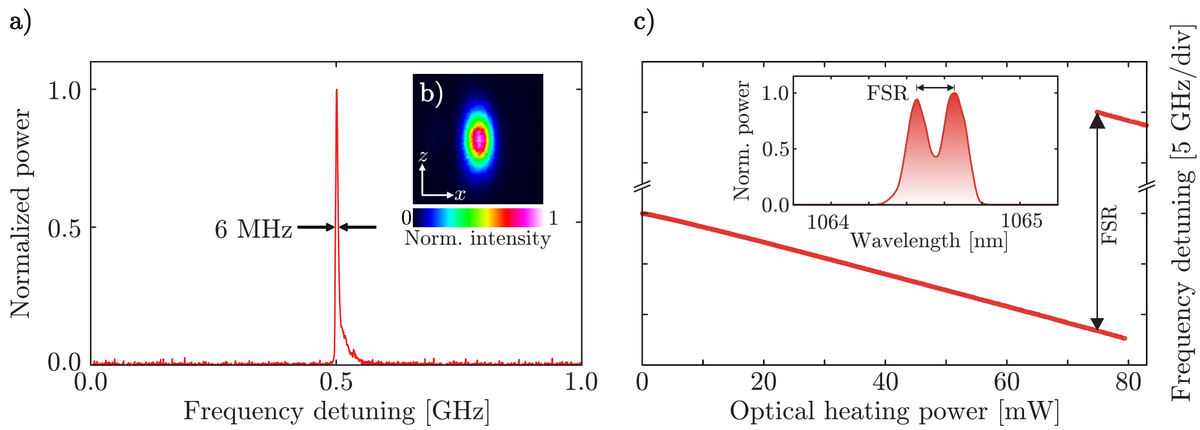

Figure 4. Transmission of the laser light generated in the whispering gallery resonator through a scanning Fabry-Pérot interferometer with 1.0 GHz free spectral range (a). Transverse intensity pattern of the generated laser light at 1064 nm wavelength (b). Frequency tuning of the laser light induced by varying the optical heating power (c). The inset shows dual-mode operation around 75 mW heating power. The modes are separated by one free spectral range of the whispering gallery resonator.

5. DISCUSSION

The results show stable single-frequency laser emission at mW output powers from millimeter-sized whispering gallery resonators. The oscillation thresholds are close to the ones determined by the simple estimation described above. The good agreement indicates that spatial hole burning does not play a major role here. The measured spectral linewidths in both configurations are below 10 MHz. They correspond to the resolutions of the respective interferometers used. Hence, it can be assumed, that the actual linewidths of the WGR-based lasers are even smaller.

The TEM_{00}-like intensity distribution indicates that laser oscillation is occurring in a whispering-gallery mode with fundamental polar mode number.[28] A lateral displacement of the excitation focus in z-direction leads to multi-mode laser operation including non-fundamental polar modes. This finding shows, that the lasing modes can be selected by spatially-selective excitation of the laser cavity, similar to a demonstration in polymer bottle microresonators.[19]

The dual-mode operation limiting the mode-hop free tuning range (inset of Fig. 4c) indicates simultaneous lasing of neighboring longitudinal modes. We expect, that wider mode-hop free tuning will be enabled by decreasing the major radius R of the resonator, as this will increase its free spectral range. With this, the number of longitudinal modes within the gain bandwidth of Nd:YVO_4 (about 257 GHz[29]) is reduced. Ideally, there is only one longitudinal mode within the gain bandwidth, which would require $R \leq 0.1$ mm.

It might be promising to apply geometric tuning instead of thermal tuning, which enables much faster tuning, just by applying a voltage to an embedded piezo actor inside the WGR.[26] Even faster tuning could be achieved by electro-optic tuning which is, however, not feasible in the materials used in the experiments described above. A suitable laser-medium which shows the Pockels effect can be neodymium-doped lithium niobate, which has proven to be an excellent medium not only for WGR-lasing but also for WGR-based self-pumped frequency conversion.[15,30] With this, the functionality of single-frequency WGR-lasers could be improved greatly by geometric or electro-optic tuning and parametric frequency conversion in a single microresonator.

The simplicity of the arrangement, the high level of integration, and the robustness make such non-resonantly side-pumped WGR lasers attractive for many applications, e.g. as the light source for handheld spectrometers.

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