Simulation of Near-IR and Mid-IR Cascade Raman Microlasers Based on Bismuth-Modified Tungsten-Tellurite Glass

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***Abstract*— We theoretically investigate cascade Raman generation in bismuth-modified tungsten-tellurite glass microlasers, for the first time for microcavities based on TeO_2 glasses. The calculated results demonstrate the opportunities of CW Raman generation in the near-IR and mid-IR ranges with CW pump at the wavelength of 1.55 µm. The predicted wavelengths are 1.81 µm, 2.17 µm, 2.70 µm, and 3.59 µm for the 1st, 2nd, 3rd, and 4th Raman orders, respectively. The diagram of power thresholds was calculated, as well as the output powers as functions of the pump power and detuning between the pump frequency and the corresponding microcavity eigenfrequency.**

I. Introduction

Raman glass fiber lasers allow obtaining radiation in spectral ranges inaccessible to fiber lasers generating at the radiative transitions of rare-earth ions. In Raman lasers, due to inelastic light scattering, the pump wavelength is converted to the low-frequency region. For CW Raman lasers, the shift of the generated frequency with respect to the pump frequency $\Delta\nu_R$ depends on the glass properties. In addition, cascade Raman generation can be reached when Raman wave itself serves as a pump for generation of the next order [1]. Thus, the 2nd-order Raman wave is shifted by $2\Delta\nu_R$ relative to a pump, the 3rd-order wave is shifted by $3\Delta\nu_R$, and so on.

TeO_2-based glasses have large Raman gains, which are 2 orders of magnitude higher than for silica glass, and the maximum of the Raman gain spectrum is shifted by $\Delta\nu_R$ = 20-28 THz (against 13.2 THz for silica glass) [2]. Therefore, Raman shifters based on TeO_2-based fibers (transparent up to ~5 µm) allow obtaining CW light at wavelengths >2 µm [3], and potentially in the mid-IR with a pump at 1.55 µm.

In addition to Raman fiber lasers, low-power microcavity lasers (microlasers) are also of interest for many applications [4]. Such a microlaser is a microsphere at a fiber end. Light propagates along the equator of this sphere in the form of whispering gallery modes [4]. To date, Raman microlasers were demonstrated on the basis of silica [5,6,7], chalcogenide [8,9], and other glasses. However, Raman microlasers based on TeO_2 microcavities have not yet been published. The main reason may be insufficiently high Q-factors of reported samples. Most recently, we reached a record high Q-factor for TeO_2-based microcavities, due to which cascade Brillouin lasing up to the 4th order was demonstrated [10]. In samples with similar characteristics, we hope to obtain cascade Raman lasing as well. The purpose of this work is to simulate cascade Raman microlasers in the near- and mid-IR range pumped at 1.55 µm. We consider bismuth-modified tungsten-tellurite glass with promising parameters for Raman generation [11].

II. Methods

To describe cascade Raman lasing we used time-dependent coupled equations [12]:

$$\frac{db_0}{dt} = \left(i\Delta\omega_0 - \frac{1}{2\tau_0}\right) b_0 - g_1 \frac{\nu_0}{\nu_1}|b_1|^2 b_0 + \sqrt{\xi_0}E_p \qquad (1)$$

$$\frac{db_j}{dt} = -\frac{1}{2\tau_j} b_j + g_j|b_{j-1}|^2 b_j - \frac{\nu_j}{\nu_{j+1}} g_{j+1}|b_{j+1}|^2 b_j \qquad (2)$$

for j = 1,…, N–1,

$$\frac{db_N}{dt} = -\frac{1}{2\tau_N} b_N + g_N|b_{N-1}|^2 b_N, \qquad (3)$$

where $b_{j>0}$ is a slow varying intracavity field amplitude of a Raman wave of order j at a frequency $\nu_{j>0}$, b_0 is an intracavity field amplitude at a pump frequency ν_0, N is a maximum Raman order, E_p is a pump field amplitude, $P_p = |E_p|^2$ is a pump power, $\Delta\omega_0$ is detuning, τ_j is a lifetime of a photon at a frequency ν_j, $\xi_j = 1/(2\tau_j)$ is a coupling coefficient, and g_j is the intracavity Raman gain coefficient. Note that $g_j = \Gamma_j g_{Te} c^2/(2n^2 V_j)$, where Γ_j = 0.7 is an overlap integral, $g_{Te} = 1.2\cdot10^{-9}$ cm/W is the bulk Raman gain for the bismuth-modified tungsten-tellurite glass [11], $n \approx 2.16$ is a linear refractive index [10], and V_j is a mode volume at ν_j.

We considered a microcavity with a diameter of 100 µm and Q-factor of 10^7 at 1.55 µm ($Q_j = 2\pi\nu_j\tau_i$), which correlates with our experimental opportunities [10]. We took $\tau_j = 8\cdot10^{-9}$ s assuming the wavelength-independent linear optical losses.

We calculated mode volumes as in [13] and obtained an almost linear dependence on wavelength (2270 µm^3 at a wavelength of 1.55 µm and 5000 µm^3 at 3.60 µm).

We considered steady-state regimes for the system (1)-(3). The output power of the j-th Raman order is $P_j = \xi_j|b_j|^2$.

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III. Results

For the bismuth-modified tungsten-tellurite glass the maximum of the Raman gain function is observed at $\Delta\nu_R$ = 27.5 THz (916 cm^{-1} [11]). We set the pump wavelength to 1.55 µm (193.5 THz), so the frequencies of the cascade Raman orders were: ν_1 = 166 THz (1.81 µm), ν_2 = 138.5 THz (2.17 µm), ν_3 = 111 THz (2.70 µm), and ν_4 = 83.5 THz (3.59 µm). The 5th Raman order corresponding to 56 THz (5.36 µm) is out of the glass transparency range and cannot be generated.

We calculated diagrams of lasing thresholds for the Raman waves up to the 4th order (Fig. 1(a) and (b) in linear and logarithmic on P_p scale, respectively). In area I only near-IR Raman lasing of the 1st order is observed. In areas II, III, and IV the maximum Raman orders are 2, 3, and 4, respectively. Output powers of the Raman waves as functions of the pump power for detuning $\Delta\omega_0 = 2\pi\cdot50$ THz are shown in Fig. 1(c) and output powers as functions of detuning for P_p = 13 mW are shown in Fig. 1(d). We also calculated output powers of Raman waves as functions of two variables P_p and $\Delta\omega_0$ (Fig. 2). In the area where the maximum Raman order is N, the wave of order N-1 and waves of the same parity have constant powers. For mid-IR high-order Raman waves it is necessary to provide a small detuning and relatively high pump power.

So, our numerical results predict near-IR and mid-IR Raman lasing up to the 4th order in bismuth-modified tungsten-tellurite glass microcavity with realistic parameters.

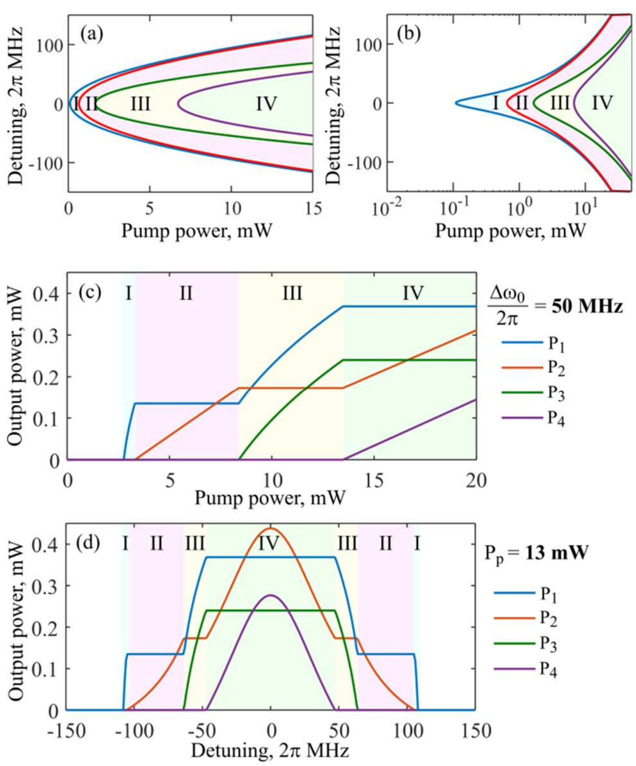

Fig. 1. Calculated diagram of power thresholds for different Raman cascades: (a) linear scale on pump power and (b) logarithmic scale on pump power. (c) Output powers of Raman waves as functions of pump ($\Delta\omega_0 = 2\pi\cdot50$ MHz). (d) Output powers of Raman waves as functions of detuning between pump frequency and corresponding microcavity eigenfrequency (P_p = 13 mW).

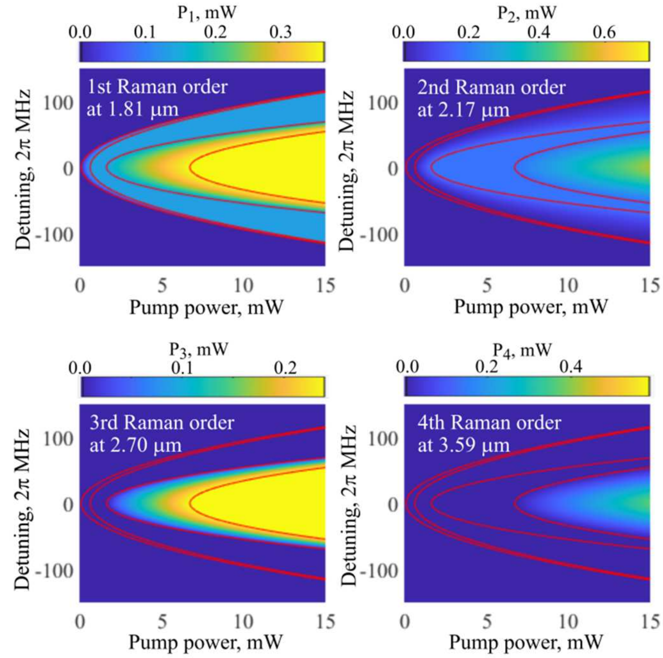

Fig. 2. Calculated output powers of Raman waves of different orders as functions of two variables P_p and $\Delta\omega_0$.

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