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論　　文　　名	「Lasing characteristics of nanocavity Raman silicon lasers」 (ナノ共振器シリコンラマンレーザの発振特性)
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論文要旨

Although silicon (Si) is used for many different types of electronic devices, its indirect band gap is problematic for certain applications. One reason is that the indirect band-to-band transition in Si results in a low radiative recombination efficiency of electron-hole pairs, and therefore the optical gain of Si is weak. Consequently, the realization of Si-based lasers using interband transitions has proven to be very difficult. To solve the problem of the lack in optical gain, the use of stimulated Raman scattering (SRS) in bulk crystalline Si has been proposed because Si has a large Raman gain coefficient and transparency for the optical communication bands in the near infrared. The SRS concept has been successfully implemented in optically-pumped Si lasers and enabled continuous-wave (cw) operation at room temperature.

Raman Si lasers can be realized with different cavity designs which provide different advantages. In 2013, Associate Professor Yasushi Takahashi, Dr. Yoshitaka Inui, Masahiro Chihara, Associate Professor Takashi Asano, Ryo Terawaki, and Professor Susumu Noda presented a Raman Si laser based on a high-quality- (high-Q)-factor photonic-crystal (PC) nanocavity with a resonator size of 10 μm and an ultralow threshold of approximately 1 μW. Such a small, low-threshold device is suited for compact sensors and also densely integrated Si photonic circuits, which can be employed for applications such as cw laser sources and all-optical switching devices.

Moreover, an essential feature for large-scale implementation in future is that the expected production costs of this device are low.

In order to expand the range of possible applications and to achieve higher performance (for example, by lowering the threshold, increasing efficiency, or increasing output power), it is indispensable to thoroughly understand the device physics of the nanocavity Raman Si laser.

However, the lasing characteristics of this type of device, *e.g.* optical gain, loss mechanisms, and lasing dynamics, have not yet been clarified.

Therefore, this thesis focuses on the lasing characteristics of nanocavity Raman Si lasers. By investigating and clarifying the lasing characteristics we can understand how to design suited nanocavity Raman Si lasers for future applications.

The specific objectives of this thesis are

- to precisely measure the Raman shift in PC Si nanocavities,
- to investigate and clarify the lasing dynamics, and
- to investigate and clarify the optical gain spectrum.

These objectives are achieved by employing microscopic Raman spectroscopy, time-domain measurements, optical gain measurements, and numerical analysis using coupled-mode theory (CMT).

Chapter 1 of this thesis presents a brief introduction to Raman Si lasers and their applications.

Chapter 2 explains the fundamentals of nanocavity Raman Si lasers. The numerical analysis of the nanocavity Raman Si laser using CMT is summarized in Chapter 3.

In Chapter 4, a precise measurement of the Raman shift of PC Si heterostructure nanocavities for Raman laser applications is demonstrated.

The nanocavity Raman Si laser with microwatt threshold utilizes two high-Q nanocavity modes to confine the pump light and the Stokes Raman scattered light.

One of the key requirements for higher performance is that the frequency spacing between these two modes matches the Raman shift of Si well, with an error less than 1.0×10^{-2} THz taking into account for the full width at half-maximum of the Raman gain of Si which is ~0.1 THz.

However, it is well known that the reported values for the Raman shift of Si vary within a certain error range due to local sample heating caused by absorption of excitation laser light, long measurement times, and temperature fluctuations of the surrounding air. Previously reported values for the Raman shift of Si lie in the range of 15.59 ± 0.03 THz (520 ± 1.0 cm^{-1}).

Therefore, in this thesis we utilize near-infrared excitation by a laser with a wavelength of 1.42 μm, which allows us to avoid local sample heating. Additionally, we exploit the two high-Q nanocavity modes to calibrate the Raman frequency. The obtained precise value for the Raman shift of Si in the PC nanocavity is 15.606 THz (520.71 cm^{-1}) with a small uncertainty of 1.0×10^{-3} THz.

In addition, this chapter clarifies that, a smaller detuning of the mode frequency spacing from the Raman scattering frequency leads to lower threshold, higher output, and higher efficiency.

In Chapter 5, the lasing dynamics of a nanocavity Raman Si laser are investigated.

It is commonly accepted that the output of a Raman Si laser tends to saturate for higher excitation powers because of free-carrier absorption (FCA).

The measurements in this chapter reveal that the free carriers, which are generated by two-photon absorption (TPA), induce dynamic effects during the initial lasing process. These effects can be confirmed even at the very low threshold power of 0.12 μW. At higher excitation powers, the Raman laser signal exhibits a significant reduction within a few hundreds of nanoseconds after the initial rise, followed by clear oscillations. The presented data show that the temporal behavior of the laser signal strongly depends on the excitation wavelength. The numerical simulations presented in this thesis indicate that the oscillations reflect the dynamical shift of the resonant wavelength of the nanocavity. The oscillation of the shift originates from the competition between the thermo-optic and the carrier-plasma effects, which are induced by free carriers generated via TPA.

In Chapter 6, the excitation-wavelength dependence of the optical gain in a nanocavity Raman Si laser is reported.

In order to improve the performance of semiconductor lasers in terms of threshold, output power or energy efficiency, it is important to clarify the spectral shape of the optical gain. This optical gain spectrum determines the optimum operating point at a given excitation power, and thus a convenient technique to obtain the optical gain spectrum of a nanocavity Raman Si laser is required.

This chapter demonstrates the so-called stimulated-Raman-scattering excitation (SRE) spectroscopy, which allows us to reveal the range of excitation wavelengths enabling laser operation, the excitation condition for maximum output, the shift of the gain peak, and the enhancement of the Raman gain including nonlinear optical losses. It is shown that the laser output remarkably decreases in the long-wavelength region of the cavity resonance as the excitation power increases, which has important implications for devices. Numerical simulations suggest that the optical loss due to FCA induced by TPA grows substantially above a certain threshold.

The revealed details of the gain and loss mechanisms and the information about dynamical lasing behavior, lasing stability, and optimum operating conditions enables optimal device design of this laser for future applications.

審査結果の要旨

本論文は，申請者が所属する研究グループによって 2013 年にレーザ発振を達成した”ナノ共振器シリコンラマンレーザ”と呼ばれる光励起型の近赤外小型レーザの発振特性を明らかにしたものである．本レーザは，物質に光を照射した時にわずかに生じるラマン散乱光を，フォトニック結晶高 Q 値ナノ共振器を用いて，ラマン利得を極限まで高めることで発振を達成している．一方で，このような高 Q 値ナノ共振器とラマン散乱を組み合わせたレーザの発振メカニズムには未解明な部分が多くあった．そこで申請者は，この新しく開発されたレーザの発振特性を詳細に調べ，明らかにした．具体的には，(1) シリコンのラマンシフトの高精度測定，(2) レーザ発振の時間領域測定，(3) 利得スペクトルについて議論している．得られた主な結果は，以下の項目に要約できる．

（１）本レーザは励起光とラマン散乱光を閉じ込めるために 2 つの共振モードを利用している．レーザ性能の向上のためには，この 2 つの共振モードの周波数差をシリコンのラマンシフトに正確に一致させることが重要である．本論文では，高 Q 値ナノ共振器の特徴を生かした 2 つのスペクトル測定を組み合わせることで，シリコンのラマンシフトを高い絶対値精度(±0.002 THz)で明らかにした．

（２）ラマンレーザの時間領域測定を行うことで，レーザ発振の時間変化や吸収損失の影響を調べた．その結果，励起強度や励起波長によって，レーザ出力が定常状態になるまでの過程やその値が変化することが判明した．これらの原因を特定するために数値計算を行い，強励起領域では非線形光学損失が大きくなり，レーザ出力が下がることに加えて，屈折率変化による共振波長シフトによっても出力が下がることを明らかにした．

（３）レーザ性能を向上させるためには，光利得の波長依存性を調べることが重要である．申請者は誘導ラマン散乱励起分光法と呼ばれる新しい利得スペクトル測定手法を用いて，本レーザの利得特性を明らかすることに成功した．この一つの測定法から，レーザ動作の励起波長の範囲，最大出力の励起条件，非線形光学損失を含むラマン利得などの様々なレーザ特性の詳細を明らかにすることに成功した．

以上の成果は，本レーザの将来的な応用に向けた適切なデバイスデザインの指針を与えるものとして期待される．また，申請者が自立して研究活動を行うのに必要な能力と学識とを有することを証したものである．