Low-threshold continuous-wave Raman silicon laser

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1. Introduction

2. Theoretical background
   - SRS
   - TPA and FCA

3. Experiment
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   - Experimental setup

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1. Introduction

Si Photonics offer low cost optoelectronics integration solutions

But, bulk Si is an indirect band gap semiconductor
→ Very low light emission efficiency

Using stimulated Raman scattering for amplification and lasing

Relatively high threshold power
→ Required high pump power

Improvement in the lasing threshold, slope efficiency, output power
2.1. SRS

✓ SRS: stimulated Raman scattering

- Rayleigh scattering
  - Elastic scattering

- Raman scattering
  - Inelastic scattering

Energy level

**Incident photon**:
- absorbed by material

Interaction with material lattice vibration

Photon emission:
- different energy

Frequency shift

\[ E = hv \]

\[ E = hv \]

\[ E < hv \]

\[ E > hv \]

Material absorption

Material loss

Stokes Wavelength

Anti-Stokes Wavelength

2. Theoretical Background

\[ \lambda = \nu \]

\[ \lambda = \nu \]

\[ \lambda = \nu \]

\[ \lambda = \nu \]
2.2. TPA and FCA

- **TPA (two photon absorption)**
  - Simultaneous absorption of 2 photons
  - Excite a molecule to higher energy state
  - Energy difference = E1 + E2
  - EHP generation
  - Nonlinear optical process

- **FCA (free carrier absorption)**
  - Material absorb photon
  - Carrier is excited: filled state → unoccupied state
  - Inter-band absorption: valence band → conduction band
  - FCA: in the same band
3.1. Design Consideration

- **Pump power** $I_p(z)$ along ring cavity

$$\frac{d}{dz}I_p(z) = -\alpha_p - \beta I_p(z) \cdot \frac{\sigma_{TPA} \cdot \tau_{eff} \cdot I_p(z)}{2} - \frac{\alpha_s \cdot \tau_{eff} \cdot I_p(z)}{2} - \frac{\sigma_{FCA}}{2} - I_p(z)$$

- **Round-trip gain in ring cavity** $G$(at Stokes wavelength)

$$G = \int_0^{\infty} \left[ g_r I_p(z) - 2 \alpha_s z - 2 \beta I_p(z) - \frac{\sigma_s \cdot \tau_{eff} \cdot I_p(z)}{2} \right] dz$$

- **Incident power on resonance**

$$I_{inc} = I_p(0) \cdot \frac{1 - \sqrt{(1 - A) \cdot (1 - K_p)}}{K_p}, \quad A = 1 - \frac{I_p(L)}{I_p(0)} \cdot \quad K_p : power\ coupling\ ratio, \quad A : cavity\ loss, \quad L : cavity\ length$$

- **For low-threshold, high-efficiency**

1. Reduce cavity loss
2. Optimize coupling ratio
3. Reduce carrier lifetime

- **Raman gain**

- **Linear loss**

- **FCA**

- **TPA**

- **Incident power on resonance**

- **Cavity enhancement factor of pump depends on $K_p, A$**
3.2. Fabrication

- Ring-cavity configuration and waveguide cross-section

**Design requirements**
- For low-threshold, high-efficiency
  1. Reduce cavity loss
  2. Optimize coupling ratio
  3. Reduce carrier lifetime

- W : 1.5μm
- H : 1.55μm
- d : 0.7μm
- Racetrack-ring length : 3cm, 1.5cm
- Bus waveguide : 1.6cm

- Coupling length : varied 700~1100μm
  - To obtain desired coupling ratio

- Reverse biased p-i-n diode
  - To reduce free-carrier lifetime
  - Need to optimize dopant implant condition
3.3. Experimental Setup

To optimize lasing condition, the Stokes wavelength is outside the WDM filter's window. This is achieved by using a coupled bus waveguide with a frequency shift and cavity enhancement effect. The laser output is coupled into the bus waveguide using a lensed fiber. A long wavelength pass filter is used to block residual pump light.
4.1. Results

- **3cm cavity case**

  - As bias is increased: laser output is increased (∴ sweep out carrier efficiently)
  - As bias is lowered: laser output saturate earlier (∴ longer carrier lifetime)
  - Threshold change only slightly (∴ TPA much weaker at low pump power)
  - 0V is applied: can still operate (∴ reduced loss and lifetime)

- Coupling ratio (0.3, 0.12)

- Reverse bias: 25V

- Lasing threshold and slope efficiency depend on coupling ratio for pump and signal wavelength

- S.E = 23%, Threshold > 40mW
- S.E = 5.4%, Threshold < 20mW

- 4. Result and Conclusion
4.2. Results and Conclusion

- **Raman Si laser spectrum**
  - Pump laser at 1430.5nm, lasing at 1545.5nm
  - Side-mode suppression ratio > 80dB
  - Laser spectral linewidth < 100kHz

- **1.5cm cavity case**
  - Lasing performance can be optimized by adjusting coupling ratio
  - Lasing can also be achieved in smaller cavity with no bias
  - Realization of low-threshold and zero-power-consumption Si Raman laser
  - Demonstrate performance of low threshold and high output power
  - Also delivers spectral purity
  - No-voltage, all-optical laser are particularly attractive: remote sensing application
Thank you
Question and Answer