

# **Defect-based Photonic Crystal Cavity for Silicon Laser**

*Final Term Paper for Nonlinear Optics  
PHYC/ECE 568*

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## **Abstract**

Photonic crystals because of their flat dispersion diagram and high quality factor cavities due to their long photon life time enhance optical nonlinearities. In this report, another degree of freedom, offered by photonic crystals is utilized to enhance Raman gain in Silicon-based photonic cavities. This is important because it leads to a decrease in lasing threshold made out of such cavities.

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# 1 Introduction

Nonlinear optics in microcavities is important not only from a theoretical point of view, but it has numerous applications in the emerging technologies. Optical switches based on nonlinear processes in materials can reach speeds that are not achievable by electronic switches and Raman lasers on silicon provide a platform for a CMOS compatible photonic integrated circuit. Optical microcavities help in design and implementation of more compact circuits and will decrease the power consumption in such circuits.

Waveguides and cavities made in photonic crystal slabs can tightly confine light. This together with waveguide's flat band dispersion diagram and the cavity long photon life time can enhance the nonlinear interaction of light and matter. This report however, focuses on how the ability to design defect-based photonic crystal cavity resonances can be exploited to design efficient laser cavities with stimulated Raman scattering providing gain. This report is organized as following: First a brief introduction to photonic crystal is given. Next the theory of Raman gain in silicon is reviewed, and in the end the defect-based photonic crystal cavity design is given and how it helps to reduce the lasing threshold is analyzed.

## 2 Photonic Crystals

### Introduction

Photonic crystals are fabricated structures whose refractive indices are modulated periodically. This periodicity can be achieved in one dimension, two dimensions or three dimensions in which case are called 1D, 2D and 3D lattices, respectively.

Electromagnetic wave inside a photonic crystal will experience a periodic refractive index, the same ways as an electron goes through a periodic potential in a solid state crystal. The periodicity in refractive index of the structure results in opening of photonic bandgap, like the electronic bandgap in materials, in which any photons with frequency within the bandgap is prohibited from propagating in the photonic crystals. Figure 1 is an illustration of 1D, 2D and 3D lattices that has been deployed in realization of photonic crystals so far[1].

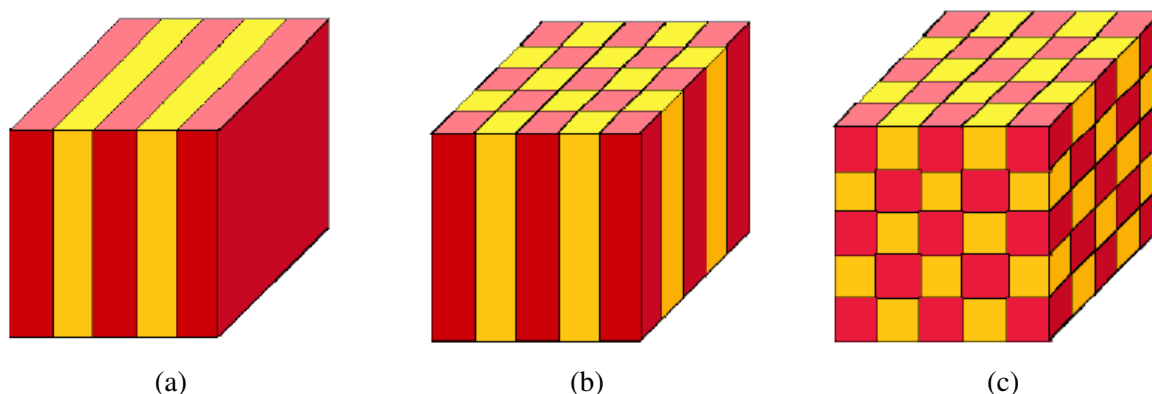


Figure 1: (a)1D lattice or a periodic stack of two materials, (b)2D lattice and (c)3D lattice

Three dimensional photonic crystal are hard to realize in reality, but two dimensional photonic crystals are relatively easy to fabricate with the help of mature silicon fabrication processing available in microelectronic industry.

## Nonlinear optics in Two Dimensional Slab Photonic Crystals

Two dimensional photonic crystal slabs are periodic array of holes drilled into a dielectric slab. Creating a defect into such a periodic lattice, can form states that can act as a waveguide or a localized state. The common feature of such defect modes is the tight localization of the optical mode to the defect and slab. This strong localization is favorable in nonlinear optics, because it helps better overlap between the electromagnetic waves taking part in the nonlinear process, resulting in a more efficient nonlinear process.

An additional enhancement of nonlinear processes in photonic crystal devices is also possible. This enhancement originates from small group velocity ( $v_g = \partial\omega/\partial\beta$ ). Physically, the small group velocity in photonic crystals is due to photons experiencing multiple scattering in these microstructures, resulting in an effective smaller group velocity. Thus, the interaction between the photons and the nonlinear material increases. It has been shown that the efficiency of nonlinear processes such as stimulated Raman scattering improves inversely with group velocity. Figure 2 shows a dispersion diagram for a 1-row missing photonic crystal slab waveguide in a triangular lattice. As can be seen, the dispersion diagram can be engineered to achieve almost any group velocities. Group velocities as low as  $10^{-2}c$  has been demonstrated in photonic crystal waveguides[2].

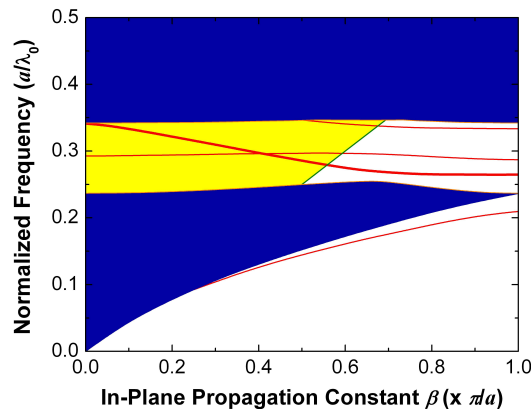


Figure 2: Dispersion diagram for a one-missing-row 2D photonic crystal slab (red curves) superimposed on 2D photonic band structure. The blue region corresponds to 2D photonic crystal propagating modes, and the white region is the bandgap.

### 3 Raman Gain in Silicon

Silicon photonic has attracted a lot of attention due to its potential for inexpensive integration of photonic and electronic circuits on a chip. However, light generation and amplification has long hindered such an integration because of inefficient radiative recombination of carriers in silicon due to its indirect bandgap. Previously, there has been efforts to provide optical gain nitride-rich silicon, Si/Ge and Si/SiO<sub>2</sub> superlattices, but none of those approaches have been succesful to date. A totally different approach based on Raman gain in silicon was suggested by Jalali *e.tal.*. Stimulated Raman scattering (SRS) was successfully used towards the first demonstration of silicon laser[3]. In this section, a brief overview of Raman gain in silicon is given.

In Raman scattering, the incident photon energy (pump beam) can excite vibrational modes of the molecules, yielding scattered photons which are diminished in energy by the amount of the vibrational transition energies. A spectral analysis of the scattered light under these circumstances reveal spectral satellite lines below the Rayleigh scattering peak at the incident frequency. Such lines are called Stokes lines. The vibrational transtion energy for silicon has been measured and is found to be 15.6 THz. Figure 3 shows the Raman spectrum of silicon. It shows both the first order Raman scattering and the second order as well[4].

The phonon spectrum of silicon consists of three optical branches that are degenerate at the zone

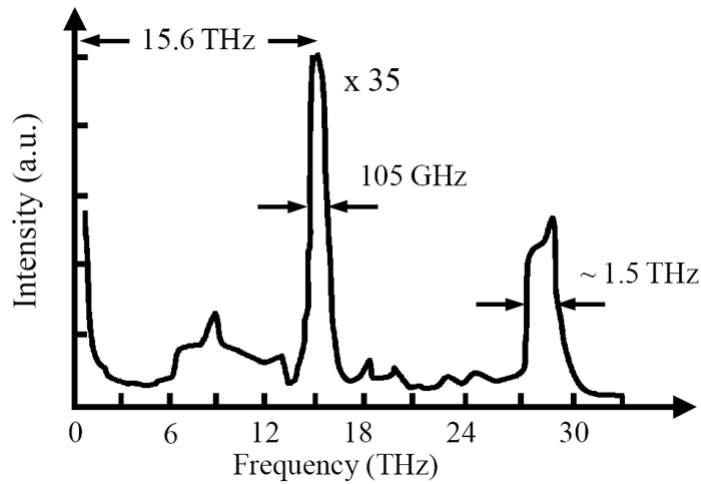


Figure 3: 1<sup>st</sup> and 2<sup>nd</sup> order Raman

center. Conservation of momentum requires that only the phonon at the zone center contributes to Raman scattering. So when calculating the polarizability of silicon at the Stokes frequency due to pump  $\vec{P}(\omega_s, \omega_p)$ , the contribution from all three branches should be included. First-order Raman scattering efficiency, is the linear term in Taylor series expansion of polarizability in terms of phonon amplitude:

$$P_i(\omega_s) = \epsilon_0 \frac{1}{V_p} \frac{\partial a_{ij}}{\partial u_{\lambda,k}} u_{\lambda,k} E_j(\omega_p)$$

where  $u_{\lambda,k}$  is the  $k_{th}$  vector component of  $\lambda_{th}$  optical phonon branch at the zone center and  $V_p$  is the primitive unit cell volume. The derivative of polarizability tensor is known as Raman tensor,

$\hat{k}_p, \hat{k}_s$	$\hat{e}_p$	$\hat{e}_s$	Relative Raman efficiency
[011]	[01 $\bar{1}$ ]	[100]	$S_0$
[011]	[01 $\bar{1}$ ]	[01 $\bar{1}$ ]	$S_0$
[11 $\bar{2}$ ]	[111]	[111]	$4S_0/3$
[111]	[1 $\bar{1}$ 0]	[11 $\bar{2}$ ]	$2S_0/3$
[111]	[11 $\bar{2}$ ]	[11 $\bar{2}$ ]	$S_0$
[0 $\bar{1}$ 1]	[011]	[100]	$S_0$
[11 $\bar{2}$ ]	[1 $\bar{1}$ 0]	[111]	$S_0/3$

Table 1: Raman scattering efficiency for some common configuration

and contains the selection rules.  $\vec{P}_i$ , the induced polarization due to the  $i^{th}$  component of photon displacement vector is:

$$\vec{P}_i(\omega_s) = \epsilon_0 \chi_R \overleftrightarrow{R}_i \cdot \vec{E}(\omega_p)$$

where all the coefficients are grouped together in  $\chi_R$ . The scattering efficiency is expressed as:

$$S = S_0 \sum_{n=x,y,z} |\hat{e}_s \cdot \overleftrightarrow{R}_i \cdot \hat{e}_p|^2, S_0 = \frac{k_0^4}{32\pi^2 n} V \chi_R$$

where  $\hat{e}_s$  and  $\hat{e}_p$  are the polarization of the scattered beam and the pump beam, respectively.  $k_0$  is the wavevector of the Stokes beam, and  $V$  is the volume of the medium. Table 1 shows the common configuration for Raman scattering in silicon[4].

What has been discussed so far, Spontaneous Raman Scattering, is a linear process. However, stimulated Raman scattering (SRS) which is responsible for providing gain in silicon is a parametric process by nature, the pump beam and Stokes beam act as a driving force for lattice vibrations, inducing a transition at Stokes frequency. The pump signal coherently transfers energy to the vibrational modes and loses intensity. The modes then transfer energy to the Stokes signal, which grows. This coupling between the Stokes and pump beam can be best described by the following coupled equations:

$$\begin{aligned} \nabla \times \nabla \times E_p + \frac{\epsilon_p}{\epsilon_0 c^2} \frac{\partial^2 E_p}{\partial t^2} &= -\frac{1}{\epsilon_0 c^2} \frac{\partial^2 P_{NL}^{(3)}(\omega_p)}{\partial t^2} \\ \nabla \times \nabla \times E_s + \frac{\epsilon_s}{\epsilon_0 c^2} \frac{\partial^2 E_s}{\partial t^2} &= -\frac{1}{\epsilon_0 c^2} \frac{\partial^2 P_{NL}^{(3)}(\omega_s)}{\partial t^2} \end{aligned}$$

where  $E_p$  and  $E_s$  are the pump and Stokes electric fields, respectively.  $P_{NL}^{(3)}(\omega_p)$  and  $P_{NL}^{(3)}(\omega_s)$  are medium third order polarizability:

$$\begin{aligned} P_{NL}^{(3)}(\omega_p) &= 6\epsilon_0 \chi_{ijkl}^{(3)}(\omega_p) E_s E_s^* E_p \\ P_{NL}^{(3)}(\omega_s) &= 6\epsilon_0 \chi_{ijkl}^{(3)}(\omega_s) E_p E_p^* E_s \end{aligned}$$

## 4 Defect-based Photonic Crystal Raman Laser in Silicon

In the last two section, it was argued that 2D photonic crystals slabs can enhance nonlinear processes in material both by confining the electromagnetic wave within the slab within sub-wavelength dimension, and also slowing the wave, increasing the interaction time of the wave with material. Also the basics of stimulated Raman scattering in silicon was reviewed. Another degree of freedom exclusively offered by the photonic crystal is presented in this section, and this freedom is used to design a cavity for efficient Raman lasing in silicon slab photonic crystal cavity. By including other terms describing two photon absorption and cavity loss, the nonlinear coupled equations given in the previous section describe the dynamics of Stokes and pump beam in a cavity. Field accumulation of both  $E_p$  and  $E_s$  within a cavity enhances both spontaneous and stimulated Raman gain. The condition for lasing achieved by equating the round trip Raman gain to the net loss in cavity. Thus  $P_{th}$  is given by[5]:

$$P_{th} = \frac{\pi^2 n_s n_p}{g_s \zeta \lambda_s \lambda_p} \frac{V_m}{Q_s Q_p}$$

where  $V_m$  is the effective cavity mode volume,  $Q_{s,p}$  cavity quality factors,  $\zeta$  spatial modal overlap,  $n_{s,p}$  the refractive index of silicon at Stokes ( $\lambda_s$ ) and pump ( $\lambda_p$ ) wavelengths and  $g_s$  the Raman gain, respectively. As illustrated, the threshold pump power scaled as  $V_m/Q_s Q_p$ . This is basically the motivation for design of small mode volume, high quality factor cavity at both pump and Stokes beam. In two dimensional photonic slabs, high quality cavities has been designed, and experimentally demonstrated by perturbing a small part of the periodic lattice. This perturbation results in a localized state in the photonic bandgap. Quality factors in excess of 500,000 has been realized. These cavities have optical mode volumes on the order of a few  $(\lambda/n)^3$ [6]. Defect-based photonic crystal cavity design, allows one to design cavities with precise resonances spectral position and engineered mode profile. This is beneficial, because a cavity with two resonances apart by silicon optical phonon frequency (15.6 THz), and high spatial modal overlap decreases the threshold pump power of the Raman laser.

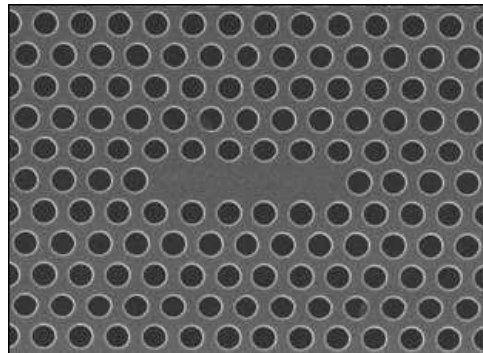


Figure 4: SEM image of a fabricated  $L_5$  cavity

In fact such a cavity has been designed. Figure 4 shows an SEM image of a such cavity. This cavity ( $L_5$ ) is formed by removing five holes out of a triangular two dimensional photonic crystal

slab. The inner holes adjacent to the row defect are shifted outward by an amount  $S_1$ . To align the bandgap around, 1550 nm, which is wavelength of interest, lattice period is chosen to be  $a=685$  nm, and to align the two even modes spectral separation to coincide with silicon optical phonon (15.6 THz), the two inner holes are shifted outwards by  $S_1 = 0.15a$ . The only two even resonances were chosen, to maximize the spatial modal overlap. Figure 5(a) and (b) show the spatial mode distribution of Stokes and pump beam. both modes have even symmetry.

Figure 6 shows the resonant frequencies of the pump and stokes beam obtained by 3D finite difference time domain method (3D FDTD). The difference of the modes is equal to the silicon phonon frequency.

The estimated threshold power for this specific design is  $344\mu W$ . This threshold pump power is on the same order of the reported threshold pump powers for other kind of high Q cavities like microtoroids and microspheres. This is promising because the quality factors for this design, are moderate (10,000)[5].

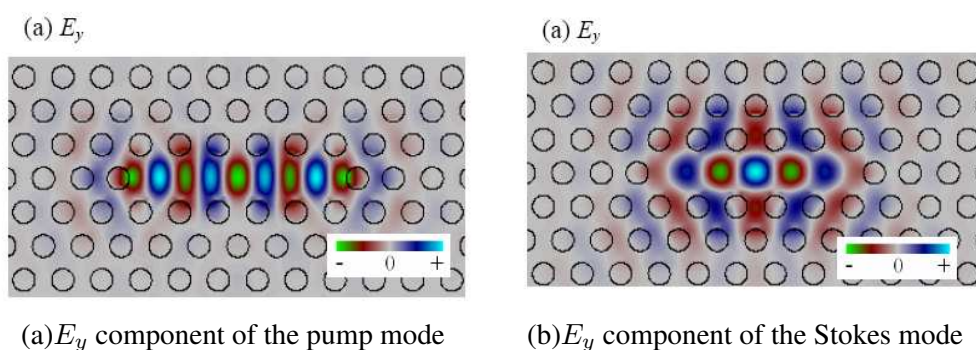


Figure 5: (a)1D lattice or a periodic stack of two materials, (b)2D lattice and (c)3D lattice

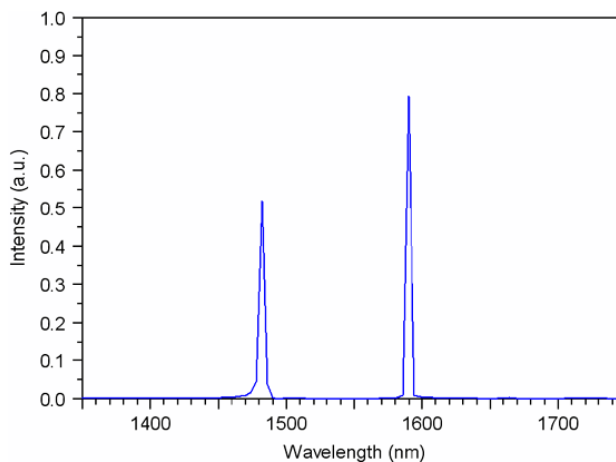


Figure 6: Calculated resonance spectrum of the proposed photonic crystal  $L_5$  cavity



## 5 Conclusion

In conclusion, defect-based photonic crystal slab cavities was analyzed to achieve low lasing threshold pump power for a Raman laser in silicon.

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