Photonic Crystal based Pulse Amplifier at 400nm

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Abstract: A 'T-shaped' defect is introduced in a two-dimensional photonic crystal lattice made of silicon, and for a small-signal optical input, this structure thus acts as an optical amplifier. A detailed analysis yields optimal linear and nonlinear performance of the optical amplifier operating in the visible region with minimal leakage and distortion.
Keywords: Photonic crystal, Photonic Bandgap, Optical Amplifier, All-optical transistor.

1. Introduction

In this era of high speed communication and computing that witnesses ever-increasing data rates, signal attenuation is always on the rise. This emphasizes the need of amplification, which, in the ideal case would add negligible distortion, and would amplify with sufficiently high gain. Extensive work has been reported in the literature on electronic and optical amplifiers [1,2]. Photonic crystals have found an exclusive place with regard to all-optical computing [2]. Photonic crystals are well known for their high nonlinearity, and as such have seen wide range of applications from photonic crystal fibers for communications, to photonic crystal-based sensors [2]. This paper portrays an optical amplifier operating at visible wavelengths, with negligible distortion, by employing and designing photonic crystals.

In general, photonic crystals constitute a lattice of rods in air, operating on the principle of photonic bandgap, and by innovative defect arrangements one can guide light suitably, and based on light interaction phenomena such as diffraction, light amplification can be achieved. Since photonic crystals inherently operate on the photonic bandgap phenomena, they act as wavelength-filters, and such filter-amplifier combination finds extensive use in various bio-related sensing applications. As an example, a photonic crystal biochemical sensor used for detecting presence of a chemical as reported in [3] can be used in conjunction with a photonic crystal amplifier, as reported in this present work. The resulting amplifier-sensor can be used for detecting the amount of chemical, and not merely its presence.

As photonic crystals offer a plethora of applications ranging from sensing to telecommunications [4–9], where signal amplification with minimum distortion plays a key role, the present paper purports to the designing of a general purpose optical amplifier operating in the visible region with optimal performance and minimum leakage and signal distortion. This forms the main result of the paper.

2. Design

The band-gap diagram, a dispersion relation between angular frequency ω and the wave vector k is as shown in Fig.(1).

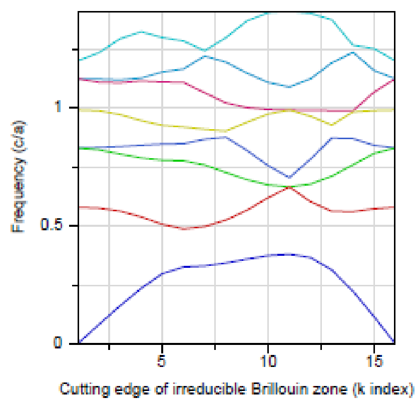

Fig. 1. Photonic Band-Gap Diagram

This diagram is based on a square lattice of silicon rods in air, where the radius of the rods are 60nm and the spacing of the rods are 500nm.

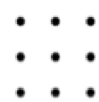

Fig. 2. Lattice Structure as obtained from MEEP Photonic Bandgap Simulation

The above mentioned lattice is shown in Fig.(2). Lattice structures of sub-100nm dimensions have been experimentally fabricated and reported in [10]. One observes a significant band-gap between band 1 (corresponding to a/λ value of 0-0.38) and band 2(corressponding to value of 0.48-0.55), where the propagation constant k has a value of 11. The structure operates at the band-gap corresponding to a/λ value of 0.4, where "a" is the lattice constant and λ are the appropriately available operating wavelength which is obtained as λ = 400nm in the visible region, corresponding to the violet regime.

The designed structure has a ‘T’-Shaped line defect guiding light at the above mentioned wavelength. Each branch of the ‘T-structure’ is 10 lattice units long. The phase delay of propagation through this length can be described using the expression $\phi = (2\pi La/\lambda)+\pi = 7.51\pi$. Based on these calculations, the geometry of the ‘T-structure’ is defined using the option of “polygons” available in the package Python-Meep [11], which in turn is based on the MIT open source FDTD software MEEP [12] and is presented in Fig.(3).

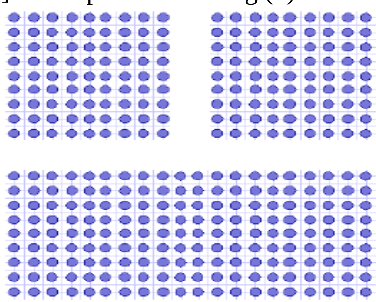

Fig. 3. Structure of the Optical Amplifier as obtained from Python-MEEP Simulation

The output of the MEEP code is a “HDF5” file, which contains spatial and temporal information about the electric and magnetic fields. This file is then read using a MATLAB code and the corresponding surface plots are obtained.

3. Results

The input signal is a Gaussian pulse with a FWHM pulse width of 150fs. This represents the signal to be amplified, and is typically of a low value (10 to 20% of the pump amplitude). The pump is launched from the vertical end of the ‘T-structure’, and is a Gaussian pulse. The output is taken from the port labeled “Output”. This represents the amplified pulse, and the ratio of the amplitudes of the output to input gives the gain of the amplifier. Two cases are of low input and high input are considered, and the corresponding Input values are given, and the corresponding outputs are obtained. The surface plot corresponding to the final timestep for two input cases of (10% of Pump) and (50% of Pump) are shown in Fig.(4) and Fig.(5) respectively.

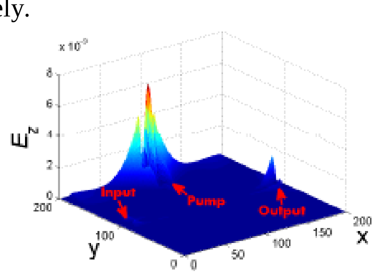

Fig. 4. Surface Plot for input signal at 0.1 pump showing Input, Output and Pump signals, at Sampling instant

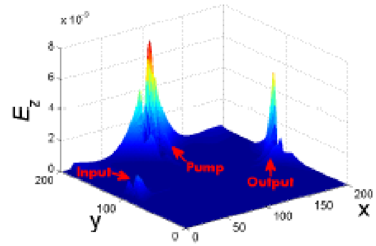

Fig. 5. Surface Plot for input signal at 0.5 pump showing Input, Output and Pump signals, at Sampling instant

The gain of the amplifier can be characterized by plotting a transfer function between the output and input field intensities. This data can be obtained numerically from the surface plots. This curve Eout(x), pertaining to 9 data points with the input value fixed at 10% of 90% of the pump amplitude, are tabulated, and a seventh-order polynomial is fitted. The coefficients are -26.59, 534, -3783, 13520, -2.694e4, 3.04e4, -1.814e4 and 4447 and the plot with residues are given in Fig. (6).

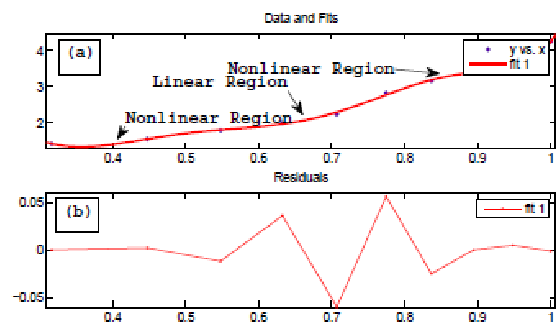

Fig. 6. Transfer function

The plot shows very close match between the fitted values and the observed values, with a reported square correlation of 99.89%. Also, the curve has three regions of operation, a linear region at 50% to 80% of pump amplitude, surrounded by two nonlinear regions on either side. The surface plot shown in Fig.(5) hence corresponds to the linear region, and the surface plot in Fig.(4) corresponds to nonlinear region of operation. These form the main results of the present work. Considering Input as port 1, output as port 2 and pump as port 3, an optical three port network can be perceived and hence the portwise performance of this optical network can be analyzed in the form of a matrix equation which is given by the relation Y=SX.
Here, the diagonal elements Sii of [S] represent the reflection coefficients of the port “i” and the corresponding off-diagonal elements Sij represent the transmission coefficients from port “j” to port “i” of the optical three port network. From the surface plots given by Figs.(4) and (5), the numerical elements of the

scattering matrix elements Sij are calculated from Eq.(3) and hence are obtained as follows:
S11=S22=0.3, S33=0.6, S12=S21=0.9, S13=S31=0.1, S23=S31=0.1.
From Eq.(4), one can judge the port-wise performance of the optical amplifier which is found to be symmetric. Of special mention are the transmission coefficients from inputs ports A and B to the output port ie S12 = S21 = 0.9 , which have high values. A leakage analysis of the amplifier structure is done by performing a two-dimensional autocorrelation trace which is plotted in Fig.(7) from which one can observe the negligible leakage throughout the designed structure.

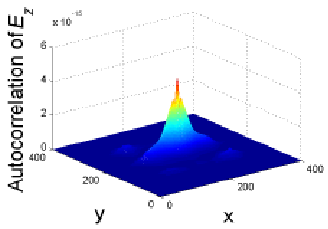

Fig. 7. Two-Dimensional Autocorrelation

In Fig.(8) the pulse amplitude is plotted as a function of time-step, each time-step being equal to 5fs. The FWHM observed is 150fs, well in agreement with the proposed design.

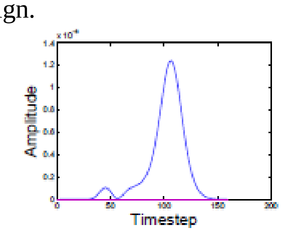

Fig. 8. Output Pulse in time-domain. Here 1 Timestep = 5fs

4. Conclusion

The main inference one can draw from the detailed analysis is that one can obtain the optimal linear and nonlinear performance of the optical amplifier operating in the visible region with minimal leakage and distortion. The proposed photonic crystal based structure is hence capable of efficient amplification, and finds a variety of applications as all-optical transistor amplifiers. One significant application of this structure is as a substitute for fiber amplifiers such as EDFA. The photonic crystal amplifier outperforms the EDFA based amplifiers when it comes to leakage and distortion, and are also smaller in size and hence cost. Moreover, since the host material is silicon, fabrication of such photonic crystal structures can be performed using existing CMOS lithographic technologies. Thus, seamless electronic-photonic integration may be achieved.

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