NOVEL, TUNABLE AND ENHANCED TERAHERTZ SOURCES USING NONLINEAR PHOTONIC CRYSTALS

J.W. Haus[1], P. Powers[1], M. Scalora[2], M. Bloemer[2], N. Akozbek[3], P. Bojja[1], M.A. Meneses-Nava[4], L.A. Aguilera-Cortes[5], M. Torres-Cisneros[1,5]

[1]*Electro-Optics Program, University of Dayton, Dayton, Ohio,45469-0245 USA*
[2]*Weapons Sciences Directorate, AMSMI-RD-WS-ST, Research, Development and Engineering Center, U.S. Army Aviation and Missile Command, Huntsville, AL 35898-5248*
[3]*Time Domain Corp, Cummings Research Park, 7097 Old Madison Pike, Huntsville, AL 35806*
[4]*Centro de Investigaciones en Optica, Loma del Pocito S/N, Leon GTO. Mexico*
[5]*Facultad de Ingenieria, Universidad de Guanajuato, Salamanca, GTO. 367130 México*
Phone: +52-464-64-80911, FAX: +52-464-6472400, e-mail: mtorres@salamanca.ugto.mx

Abstract
We proposed a coherent source based on parametric down-conversion in a photonic crystal. Our design is based on the band edge or defect-mode field enhancement phenomena near a photonic band gap. The numerical results show that a range of bandwidths, intensities, and frequencies up to 12 THz can be obtained.

INTRODUCTION

Although several new terahertz (THz) sources have been developed in the last decades, potential applications have increased the interest to find new designs. Structures, where the interfering films are arranged with thicknesses that are comparable to the wavelength of the source, are called photonic crystals or photonic band gap (PBG) structures. They are designed to exploit the special properties that occur due to the interference among the layers. For instance, light transmission can be suppressed over a specific band of frequencies or the wave dispersion can be managed to reshape pulses or phase match multiple wavelength signals in a nonlinear material environment.

In a recent publication, Yan-qing Lu[1] et. al. proposed the use of a nonlinear photonic crystal or PBG device to generate coherent microwave radiation through the optical rectification effect. They used the PBG dispersion characteristics in order to solve the phase-matching problem, but they did not consider the effects of band-edge enhancement nor did they discuss the effects of using sources at different incident angles to tune output THz radiation.

In this work, we concentrate on the same problem of generating coherent THz radiation using a PGB structure, but we focus on the local-field enhancement mechanism that is available by tuning the driving fields either to band-edge or to a defect mode in the band gap. The local-field phenomenon involves resonant field enhancement and increased density of states or equivalently the slow group velocity of the optical waves[2]. The combination of these effects can provide great flexibility in the design of new devices for sub-THz or THz wave generation. We report an enhancement that is compared against the result expected for a homogeneous GaAs material of the same thickness. We also show that the enhancement is retained and the THz radiation is broadly tunable when the two laser sources are not co-linear.

0-7803-7709-5/03/$17.00

ANALYSIS AND RESULTS

We have looked at several geometries using GaAs, as the first material and materials as AlAs, Al_2O_3 (alumina) or air as the second material. Each pair provides a larger index contrast. The final optimized structure does not rely on GaAs for the nonlinear mixing to generate radiation. Other materials such as, GaN or even poled electro-optic polymers could be incorporated into final designs, based on the availability of fabrication techniques.

The theoretical analysis involves the application of the transfer matrix method to compute the fields at two wavelengths inside the PBG structure that are detuned from one another to generate the desired difference frequency. Both driving fields are tuned near the same transmission resonance in the structure. The dispersive dielectric properties of the materials were incorporated into the program. We considered the possibility of air and GaAs substrates and comment on the effect of different substrates.

We determine the THz signal enhancement by taking the products of two fields in the sample, located at different wavelengths, integrating over the sample and normalizing with respect to the nonlinear length. The normalization is the expected low-frequency signal when the sample is perfectly phase matched in the homogeneous sample of the same length and the same nonlinear coefficient. The enhancement is compared against the result expected for a homogeneous GaAs material of the same sample thickness. Our sample is very thin compared to the THz wavelength, so the THz propagation effects are not important. The results show that the enhancement grows as the number of layers is increased; however, the bandwidth of the resonance also decreases as more layers are added. The frequency of the down-converted signal can be tuned by intersecting two non co-linear laser sources. Suppose that one laser is normally incident on the medium and the second laser is non-normally incident, which shifts the transmission maximum and the band edge.

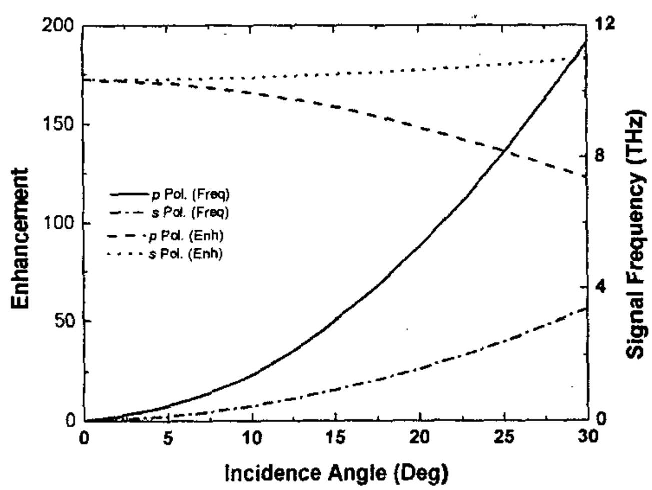

Figure 1 – Enhancement and Signal frequency versus angle of incidence for p- and s-polarizations.

At non-normal incident angles the transmission spectrum is different for p- and s-polarizations. Figure 1 highlights our results on the dependence of the THz emission with the angle tuning of the THz emission. The polarizations are degenerate at normal incidence and have their maximum near zero frequency. By tuning out to 30 degrees the signal frequency at the maximum enhancement is about 11.5 THz for p-polarization and 3.5 THz for s-polarization. The peak enhancement for both polarizations remains over two orders of

magnitude. The bandwidth of the enhancement peaks remains around 75 GHz over the entire range of angles. A localized defect mode can also be exploited as a mechanism to enhance THz signals in a PBG. It represents almost three orders of magnitude enhancement over the band-edge enhancement case. However, by using the angle tuning of one laser we found that the shift is much smaller for our defect example than it was for the band-edge case.

The power conversion efficiency can be roughly estimated for this process. Driving the THz signal with 1 mW of signal power focused to a spot area of 10^{-3} cm^2 yields an electric field amplitude around 0.2×10^4 V/m. The THz field generated in the PBG is estimated from an approximate coupled-mode equation, and the THz intensity is given by

$$I_{THz} = \frac{c\varepsilon_0}{2}\left(\frac{2\pi}{\lambda}L\right)^2 \eta\left(\chi^{(2)}E^2\right)^2 \qquad (1)$$

For our estimate of the conversion efficiency we use: a sample length: L=10 μm, generated frequency: ν=1 THz or λ=300 μm, $\chi^{(2)}$ = 10^{-11} m/V and $\eta=10^2$. The THz power generation is about 10 pW. The result scales proportional to the pump power squared, so for 1 W laser powers the THz signal will be about 10 μW. The overall efficiency is inversely proportional to the THz wavelength, so higher frequencies will be generated with higher power. A large portion (more than two orders of magnitude) of the power inefficiency is due to the quantum efficiency of the down-conversion process.

CONCLUSIONS

We demonstrated that tunable, enhanced, long-wavelength signal generation from sub-THz to several THz is attainable using either band-edge or defect effects in a second-order nonlinear PBG. By designing samples with specific numbers of layers and refractive index contrast we can tune both the bandwidth and intensity of the signal. The excitation wavelengths are determined solely by the thickness of the layers and therefore can be tuned to wherever there are available sources.

ACKNOWLEDGEMENTS

This work was supported by a DARPA grant, NSF grant ECS-0140109 and CONACyT # 010470 through the program "Estancias sabáticas en el extranjero". Also, on of the authors, MTC would like to thank Prof. Haus and EO program at UD for their hospitality.

REFERENCES

1. Yan-quing Lu, Min Xiao, Gregory J. Salamo. J. of Quantum Electronics 38 (5), 481-485 (2002)
2. M. Scalora, M.J. Bloemer, A.S. Manka, J.P. Dowling, C.M. Bowden, R. Viswanathan, J.W. Haus. Phys. Rev. A. 56 (4), 3166-3174 (1997).