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Enhanced Photocurrent Efficiency of a Carbon Nanotube Embedded in a Photonic Structure

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Abstract

One of the most rapidly-growing areas in nanoscience is the ability to artificially manipulate optical and electrical properties at the nanoscale. In particular, nanomaterials such as single-wall carbon nanotubes offer enhanced methods for converting infrared light to electrical energy due to their unique one-dimensional electronic properties. However, in order for this energy conversion to occur, a realistic nanotube device would require high-intensity light to be confined on a nanometer scale. This arises from the fact that the diameter of a single nanotube is on the order of a nanometer, and infrared light from an external source must be tightly focused on the narrow nanotube for efficient energy conversion. To address this problem, I calculate the theoretical photocurrent of a nanotube p-n junction illuminated by a highly-efficient photonic structure. These results demonstrate the utility of using a photonic structure to couple large-scale infrared sources with carbon nanotubes while still retaining all the unique optoelectronic properties found at the nanoscale.

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Contents

Acknowledgement 4
Photonic Structure Specifications 7
Carbon Nanotube Photocurrent Calculations 10
Conclusion 10
References 11
Distribution 12

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Photonic Structure Specifications

The two-dimensional photonic structure considered in this work is based on the design of Lin et al.[1] who originally used a silicon structure to couple terahertz radiation into a narrow waveguide. For the nanotube-photonic device in this report, I am primarily interested in the infrared region of the electromagnetic spectrum, so a few modifications have been made to their original design. The most significant and important modification is the use of a GaAs (= 13.2) photonic substrate which is transparent to infrared light.[2] The photonic structure studied here is a periodic square array of air holes arranged on a 48 m × 85 m GaAs slab shown in Fig. 1. The entire photonic structure is enclosed with absorbing boundary layers with 15 m of air (= 1.0) between the top boundary layer and the cleaved GaAs slab. The ratio of the air hole radius to the lattice spacing is *r*/*a* = 0.3 where *a* = 1.365 m. The corresponding band structure of this periodic array is shown in Fig. 2 for all wave vectors along the edges of the irreducible Brillouin zone defined by the points , M, and X. Using a plane-wave expansion expansion method[3], the resulting band structure was obtained for a transverse magnetic (TM) mode which has its electric field perpendicular to the plane of the GaAs slab. An effective index of 3.0 was used for the background GaAs material which corresponds to a guided mode in the slab having a wavelength of around 10.6 m.

From the band structure, it can be deduced that a wavelength of 10.6 m lies in a frequency range contained in the first band for incident light along *any* direction. By choosing the incident light to coincide with a frequency in the first band, any plane wave launched into the photonic structure will propagate with minimal transmission loss. Once the light has been guided through the photonic surface, the propagation path of the incident plane wave will be bent and altered by the pattern of air holes in the GaAs substrate.

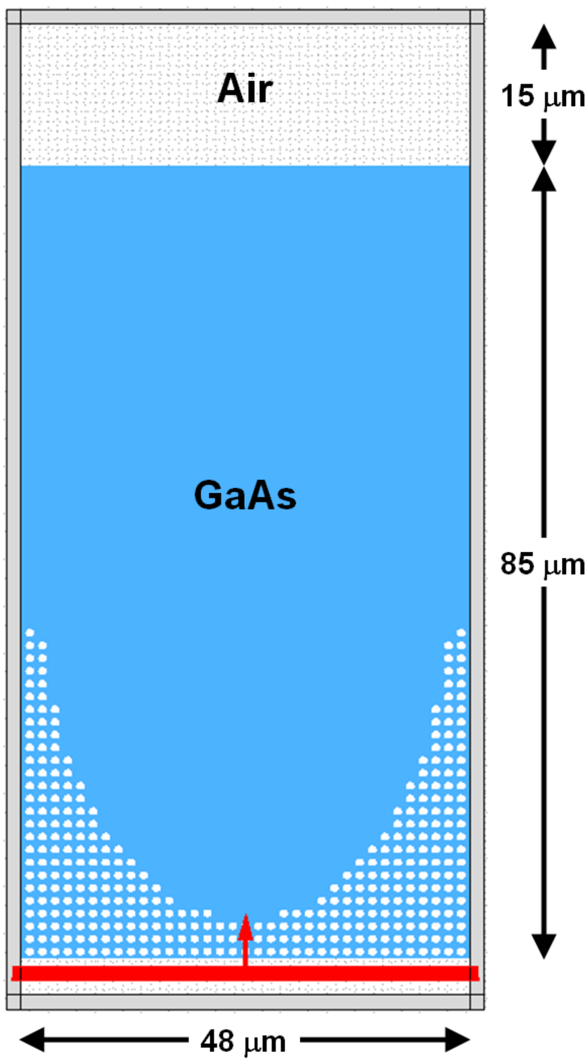

Figure 1. GaAs photonic structure enclosed with absorbing boundary layers. The ratio of the air hole radius to the lattice spacing is *r*/*a* = 0.3 where *a* = 1.365 *μ*m. A plane wave approaching the structure from below is shown in red.

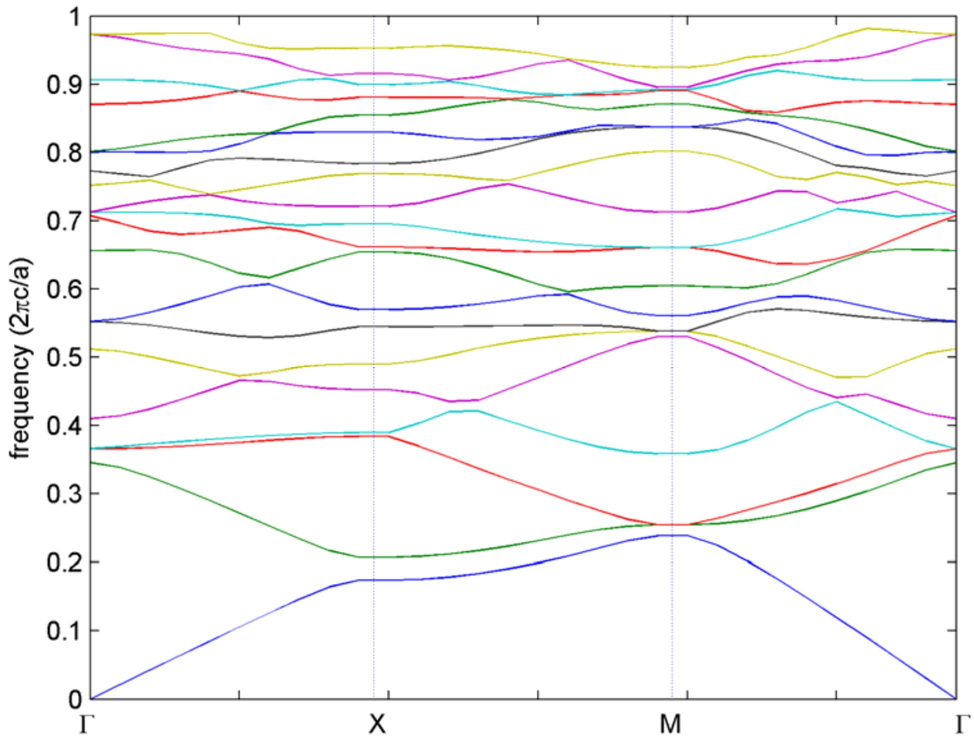

Figure 2. Calculated photonic band structure of the GaAs photonic array.
A wavelength of 10.6 μm lies in a frequency range contained
in the first band for incident light along any direction.

To investigate the focusing effects of the photonic structure, a two-dimensional finite difference time domain (FDTD) method was used to propagate Maxwell's equations in time and space throughout the entire structure.[4] A 50 m-wide input wave (10.6 m wavelength) was launched along the X direction into the photonic structure, and the steady-state electric field intensities ($\propto |E_z|^2$) are shown in Fig. 3. After passing through the array of air holes, the light propagates over several microns, subsequently focuses, and finally exits the GaAs material into air. The performance of the photonic structure can be quantitatively characterized by calculating the E_z intensity along a vertical line through the center of the structure. As shown in Fig. 3, the photonic structure tightly focuses the wide plane wave into a narrow 5- m-wide region which lies 0.1 m outside the cleaved GaAs facet. Along this line scan, the electric field intensity reaches a maximum value of 6.25 relative to the source intensity which was set to a value of 1.0. From the E_z and B_x field distributions, I also calculated a coupling efficiency of 63% by integrating the *y*-component of the Poynting vector across a 10 m wide region near the focusing point and dividing it by a similar integration across the entire 50 m source region. In other words, 63% of the input power due to the 50 m-wide light wave is focused in a 10 m wide region near the GaAs-air interface.

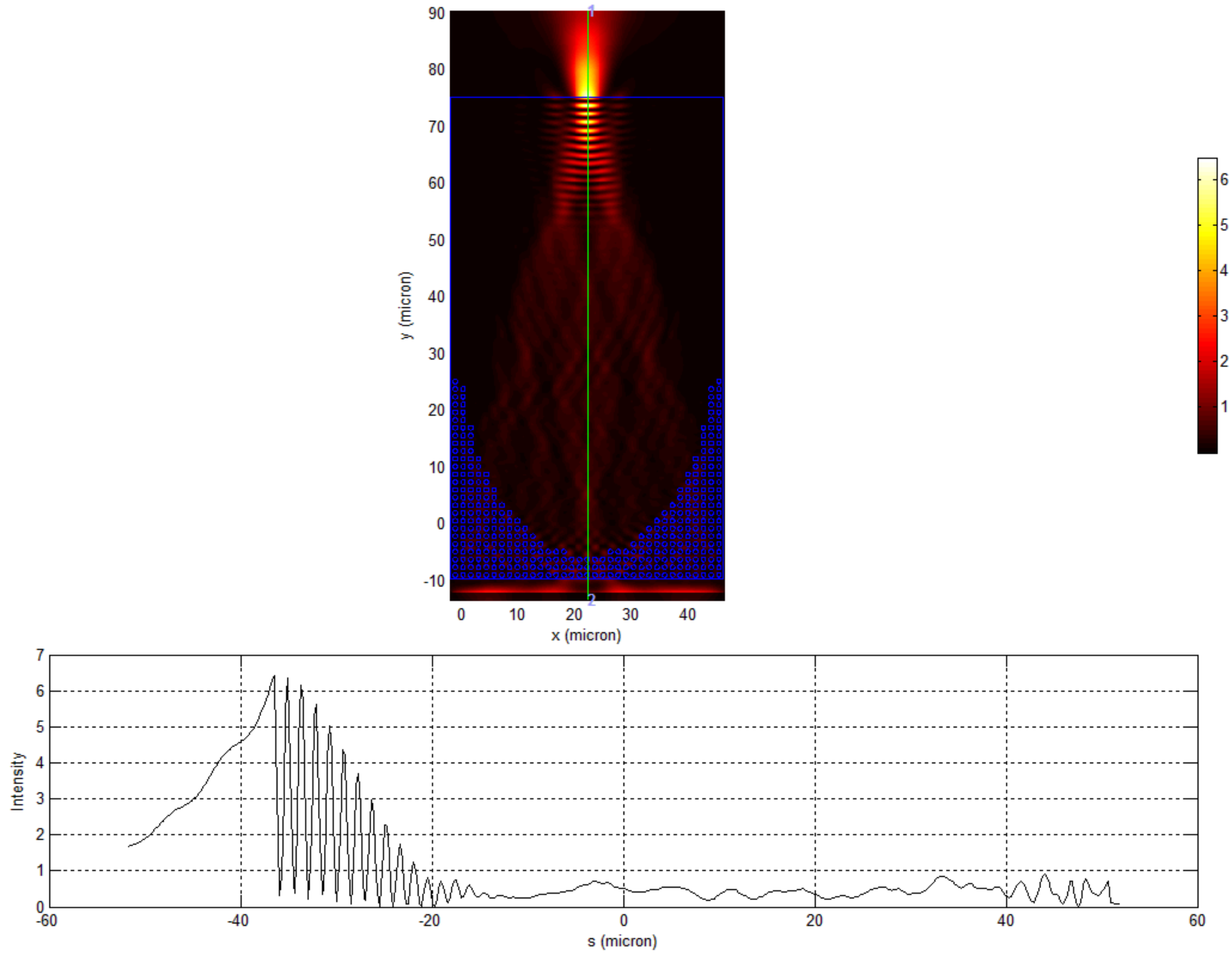

Figure 3. Intensity profile of the GaAs photonic structure obtained from a two-dimensional FDTD analysis. The *z*-component of the electric field intensity along the vertical green line is shown below. The source intensity is normalized to a value of 1.0.

It is important to mention that I also performed FDTD calculations on an uncleaved GaAs slab without the 15 m air interface and found that the intensity was significantly reduced by a factor of 2.5 compared to the present photonic structure. The increased intensity of the present configuration is mostly due to the rapid change in permittivity as the light waves approach the GaAs-air interface. Once the light finally exits the GaAs material into air, it slightly refocuses near the interface again before spreading out into free space.

Carbon Nanotube Photocurrent Calculations

The final stage in evaluating the efficiency of this nanotube-photonic device is to calculate the increase in photocurrent due to the photonic structure. Since the photonic structure is operating in the TM mode with an E_z component perpendicular to the plane of the GaAs slab, the carbon nanotube was placed near the GaAs-air interface with its axis parallel to the E_z field. In the nonequilibrium Green’s function approach at low input power, the efficiency   of a nanotube *p*-*n* junction under bias is given by[5]

$$\eta = \frac{kT}{4eI_\mathrm{s}} \frac{I_\mathrm{ph}^2}{P_\mathrm{op}} \tag{1}$$

where I_s is the saturation current of the nanotube, I_ph is the current generated by the electron-photon interaction, and P_op is the optical power delivered to the nanotube. Since I_ph depends linearly on P_op, Eqn. (1) reduces to $\propto P_\mathrm{op}$ at low optical power. Therefore, a relative intensity of 6.25 obtained via the photonic structure translates into a 525% increase in photocurrent.

Conclusion

In conclusion, I investigated the feasibility of using a photonic structure to enhance the photocurrent efficiency of a carbon nanotube device. Using a two-dimensional FDTD method, I designed a GaAs photonic structure which modulates the propagation of infrared light to focus plane waves into a 5   m-wide region. The subsequent increase in electric field intensity in this region enables the computation of power efficiency within a linear response approximation.

Although the photonic structure studied here enables a 525% increase in photocurrent, it is quite clear that this improvement is still not large enough to make a viable carbon nanotube-based photodetector. Specifically, the nanotube *p-n* junction utilized here is already a very idealized situation, and one would expect the photocurrent from a real, unmodified, carbon nanotube to be dramatically less (even in the presence of the proposed photonic structure). Furthermore, the use of a photonic structure alone to merely focus light is somewhat removed from a scientific understanding of enhancing photocurrent efficiency. Rather than enhancing light-collection efficiency via photonics, directing and controlling the electronic properties of the nanotubes themselves is a much more promising route towards the realization of efficient nanodevices.

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