



shutterstock/ASAP

Small Dimensions, Large Impact

Nano-Photonics Leads to Far Reaching Changes in Electronics and Optics

Nano-Photonics offers tremendous promise in creating super fast and stable communications and data-transfer technologies. This exciting nano frontier also shows great potential in breaking down the barriers in the field of medical imaging.

Translated and adapted from the Hebrew article by Meir Shragay and Prof. Zeev Zalevsky, published in *Galileo*, Vol. 123

For quite a few years, people have been talking about the enormous promise of nanotechnology. But while scientists, policy makers, industrialists and consumers share a justified excitement about this field's potential to create a new world of super powerful, yet tiny, devices, the fact is that manufacturing limitations have kept nanotechnology's biggest – or, shall we say, smallest – dreams from being realized. Recently, breakthroughs in our ability to manufacture stable, nano-scale structures have renewed hope that the practical application of nanotechnology is about to take a significant step forward.

Much of the advancement is occurring in the area of nano-photonics – a field which takes advantage of the unique interplay between light and ultra-small, engineered structures. This article presents an overview of the current state of nano-photonics, illustrating how this field may someday allow engineers to exceed the classical bounds of processing speed, information bandwidths and image-resolving capabilities.

A Promise to Keep

Nanotechnology aims to create devices that are both extremely powerful and extremely small; components incorporated in nanotechnological applications are significantly smaller than a millionth of a meter. Nanotechnology has become an important player in the advancement of a number of key areas in the exact and natural sciences, including the creation of new materials with particular properties, energy technologies such as advanced photovoltaic cells, and new methods for medical treatment. At the same time, scientists have begun to apply nanotechnology to the development of magnetic components, as well as structures that interact with particles of light, or photons.

This move toward integrating nano-structures with optics created an opportunity to overcome a serious obstacle in the area of communications. At the end of

the 20th century, Internet concerns were already adept at quickly transferring large quantities of data through a worldwide network of fiber optic cables. However, when the high-tech bubble burst, many Internet technology companies collapsed and development efforts slowed. Luckily, a new technological approach – based on the integration of nano-phonic components with existing optical infrastructure – is generating impressive results.

This article will focus on two areas in which nano-photonics is showing great potential. First, we will look at the role of nano-photonics in the creation of communications and data-transfer technologies that are infinitely faster and more stable than conventional systems. In addition, we will look at how nano-photonics is breaking down barriers in the field of medical imaging.

Riding the Wave – and the Particle

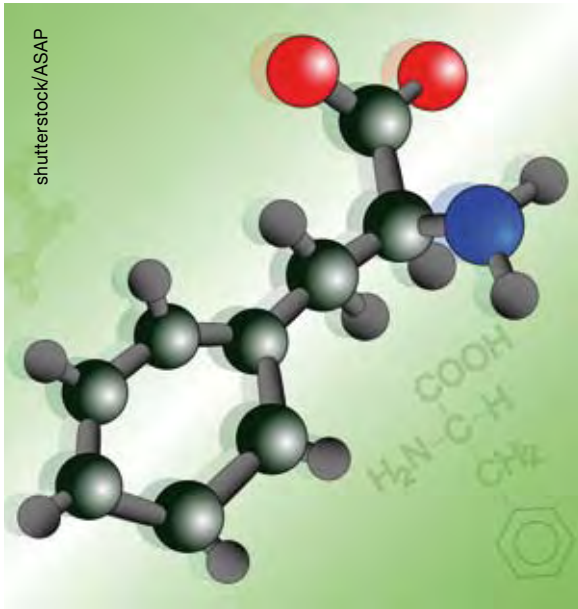
Photons are elementary particles of light. A photon has a finite quantum of energy, which is inversely proportional to the wavelength of the light it carries. The speed of light is measured as the speed of photons in a vacuum – 300,000 km per second.

Photonic processors have the potential to deliver processing rates and bandwidths that are significantly higher than conventional electronics, without overheating. This will allow a vastly more efficient use of the optical data lines currently in place.

Nano-photonics refers to the ordered movement of these particles through physical components that measure significantly less than a millionth of a meter. Nano-photonics takes advantage of the ability of light to act both as a particle and as a wave – a counter-intuitive phenomenon that lies at the basis of modern quantum mechanics. In nano-photonics, the dual nature of light can be put to work, in devices

»

>>



that take advantage of properties relating to light's particle nature – i.e., interactions and scattering – as well as the wave nature that lies at the heart of light's vulnerability to diffraction and interference.

Logic Gates and Photon Processors

The computer market is highly competitive, and competition is especially fierce in the areas of digital signal processors and electronic memories. Today, both Intel and IBM are devoting significant R&D efforts to the development of a processor based on nano-photonics.

Before beginning a discussion of photonic processors, it is important to note the achievements of conventional nano-electronics, in which components measuring as little as 45 nanometers are already in use. Yet, this astonishing miniaturization comes with a price: while more components can be squeezed onto a circuit board, this results in a serious problem of increased heat emission. Depending on the load passing through the circuits – a load that results in electrical resistance

– heat emission can measure over 150 watts, and perhaps even 300 watts under certain circumstances. Such levels of heat can irreparably damage a device, rendering it impractical.

Photonic processors have the potential to deliver processing rates and bandwidths that are significantly higher than conventional electronics, without overheating. This will allow a vastly more efficient use of the optical data lines currently in place. Unlike an electronic processor, in photonics, the heat dispersion is not connected to electric resistance. Without electrical resistance, increased information loads – and processing rates – do not result in heat. As a result, the processing rate can be significantly increased.

As compared to conventional electronics, how much faster can nano-photonic processors work? In the newest electronic processors, the current clock frequency is about 3GHz, meaning three billion “ticks” per second. That sounds impressive until you consider how low heat generation affects the potential processing rate of nano-photonic processors, which may reach higher than 1000GHz (a thousand billion times a second). In other words, a photonic processor will complete, in fractions of a second, a program that would run for hours and days using today's electronic processors.

Getting Down to Components

How is such a tremendous increase in speed and power to be brought about? First, we have to build nano-photonic components that will form the building-blocks of future devices.

All digital signal processors are based on a basic unit called a “gate” – a system that performs a logical operation on an input signal. Gates, in turn, are based on “transistors” – devices that regulate current or

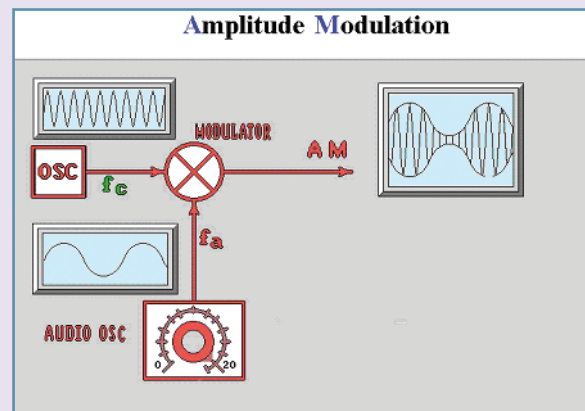
What is a Nano-Photonic Modulator?

A modulator is a device that takes data input of relatively low frequency, and installs it on an optical, “carrier” wave of relatively high frequency. Modulation can be performed in many ways, but in this example, we’ll look at Amplitude Modulation – the same transformation that is the basis of AM radio transmissions. This system is the foundation of most of the nano-photonic components mentioned in this article.

Let’s assume that an oscillator discharges a stable sine wave at a relatively high frequency. (For demonstration purposes we’ll say that the oscillation frequency is 657 KHz – the transmission frequency of “Voice of Israel” radio broadcasts on the AM dial.) This sine wave – marked in the accompanying diagram as f_c for frequency carrier – enters into the modulator on the left side.

From beneath, the modulator receives an audio signal, designated in the diagram as f_a – for illustration’s sake we’ll say that f_a is the recorded voice of the late “Voice of Israel” broadcaster, Shosh Atari, who whistles into the microphone at a clear and continuous frequency of 1000 Hz.

The modulator installs the audio signal f_a on the carrier wave f_c , so that the outcome is an AM signal



where the amplitude of the carrier wave ascends and descends according to the sound wave which is a sine wave at frequency of 1000 Hz.

Within home radio receivers, the signal is acted upon by a demodulator – also known by its more common name, a rectifier – that reverses the modulator process. The demodulator unpacks and isolates the audio signal from the AM wave, and after increasing its power, transfers the signal to the receiver’s loudspeaker. This is how we can hear the beloved voice of the late Shosh Atari, transferred to us on the back of an optical carrier wave.

voltage flow. In order to build the photonic gates that will form the heart of a photonic processor, first we need to develop an optic foundation that simulates an electronic transistor.

In photonic transistors, photonic current – that is, light – flows instead of electric current. To differentiate the light-activated transistor from transistors used in conventional electronics, scientists refer to this

component as a modulator. (For more about nano-photonic modulators, see the box above).

Optical Filters For Better Imaging

Every optical/lens system of a camera or microscope has a limited ability to separate objects. Therefore, small details that are located close to each other appear to be connected and may be seen as one big blurry item. One of the most significant research

»

>>

Optical Modulators

Researchers at Bar-Ilan University are currently collaborating with scientists from other institutes in Israel and abroad with the goal of developing several types of photonic modulators. Such modulators could be integrated into a futuristic nano-photonics-based microchip.

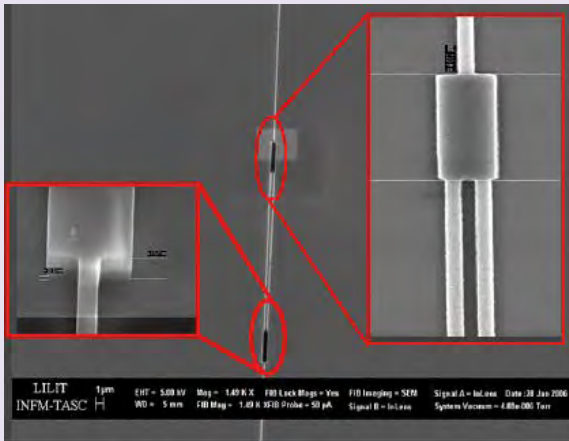
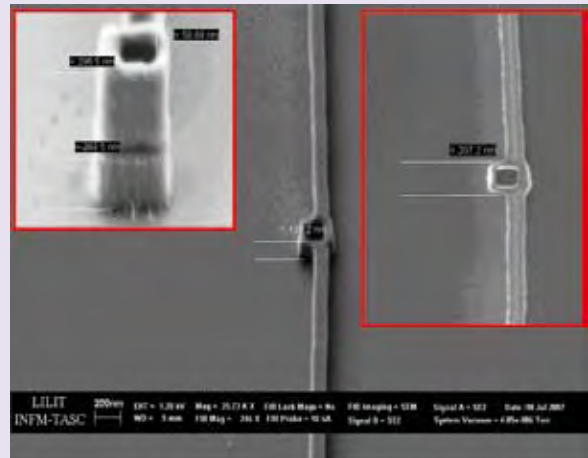


Illustration of an all-optical component, in which the signal that moves through the component, as well as the features that modulate the signal, are all photonic.

In this component, light is directed from the bottom into a single light waveguide, which then expands and splits into two waveguides. In the upper part of the drawing, the split light re-unites. A magnified view of the areas in which the waveguide widens, and where it is subsequently constricted appears on both the left and right sides of the diagram.

Where the waveguide is widened, it is constructed in such a way that the path taken by the light is slightly different in each “lane”. Therefore, when the paths are re-united, optical interference occurs, causing the light coming from both paths to cancel each other such that

no energy is output from the device. An additional light waveguide (a control signal), not shown in the diagram, then takes over. The light carried by this waveguide illuminates the widened waveguide and creates free electrons (due to the absorption of the photon energy). These free electrons alter the refractive index and the reduction coefficient of the information waveguide, creating non-destructive interference. As a result, some of the light-based information exits the component. This result resembles the description given for the AM modulation. By the applied photonic control signal we may generate modulation of the amplitude of the information signal having the photonic carrier frequency.



In this diagram, we see a component in which an optical waveguide is directed through a bucket-shaped area where a particle is sequestered. This particle is drawn out under the influence of an external electric field that acts as the modulation signal applied on the bucket area. It moves in the bucket, goes in and out of the information light space and scatters it, while at the same time prevents light from going through the device. In this illustration the information-carrying signal moves within the device from the bottom towards the top.

areas in nano-photonics concerns spatial nano-phonic components that improve the resolution of imaging systems. Now it is possible to observe small objects, and separate objects that are extremely close to each other, at a level that was not previously possible.

One of the most significant research areas in nano-photonics concerns spatial nano-phonic components that improve the resolution of imaging systems. Now it is possible to observe small objects, and separate objects that are extremely close to each other, at a level that was not previously possible.

Improving the resolution of imaging systems requires a combination of optical nano-phonic components with the lens, and optically-based digital image processing. These paired technologies can be applied, for example, to modern microscopes. They can also be applied to security and medical devices, such as cameras that detect intruders into a protected space, or the imaging components that are fitted within devices used for endoscopic surgery.

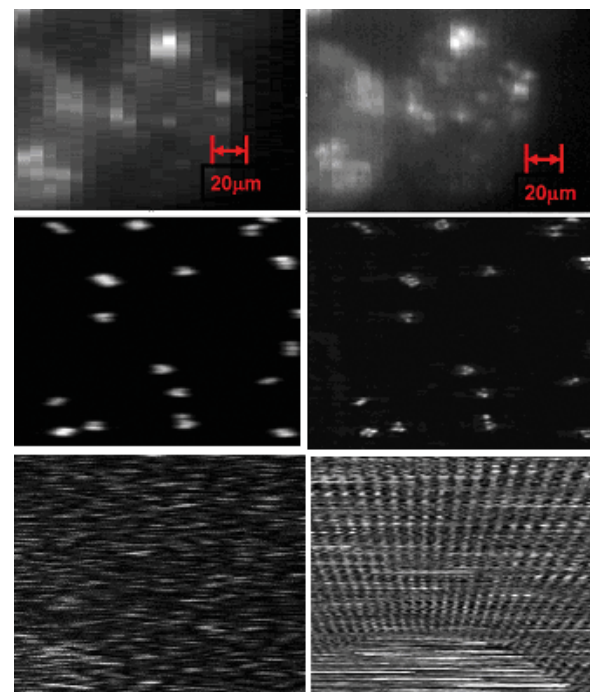
Nano-phonic enhancements to the lens can be effected through engraving, or by the creation of a certain ground surface profile. Thus, when the light wave crosses through the imaging lens or near the camera detector, its spatial scattering pattern will be known in advance. This will allow the computational reconstruction of very small objects encoded within an image. In some of the most developed methods, an optical spatial filter is designed as a separate component, one that can be used to project unique spatial patterns that help characterize the observed object. Such filtering, in combination with improved image processing, results in better image resolution.

An example of how nano-photonics can improve microscopic resolution is displayed in the illustration

below. The illustration shows three different objects, shown in the left column as observed without nano-phonic imaging methods, and on the right, with the improvement. The two upper examples are cells; the third (bottom) example is a resolution target.

In this method a spatial pattern – known in advance – is projected onto the object (our spatial filter), and moved in relation to the object. A series of low-resolution images are gathered (in accordance with the diffraction limits). The images are processed through an algorithm that takes the projected spatial pattern into account, and allows the reconstruction of the object in an improved resolution (see the right column).

In this illustration, we see a method for improving image resolution in devices used in rainy weather. In this technique, the rain not only doesn't reduce the quality of



Super resolution of object imaging in rainy conditions

>>

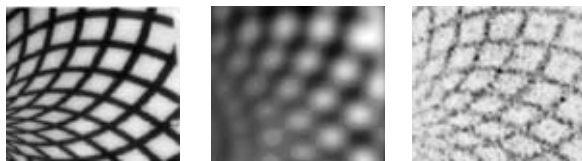
>>



shutterstock/ASAP

the image, but in fact serves to improve the resolution. The basic principle is similar to that described earlier.

Under conventional imaging conditions, raindrops are both small and in motion relative to the object, which makes it difficult to see clearly. With the assistance of digital processing of the low resolution image series we can reconstruct the location of the raindrops from each picture in a series. This digital evaluation for the locations of the raindrops is possible because although in every captured low resolution image they appear smeared and blurry, they are nonetheless sufficiently separated from each other and thus the blurred spots do not coincide. After evaluating the locations of the raindrops, we may use this digitally extracted distribution as our spatial filter or pattern (mentioned above) that assists in improving the imaging resolution.



Super resolution of objects in rainy conditions

Using this method, it is possible to examine images taken in low resolution and reconstruct small details that could not be separated earlier. On the left side our resolution target is displayed in the original resolution. The actual outcome of a blurry low quality imaging system is displayed in the center. After activating the method, a reconstruction resolution's target is created as displayed on the right side. One can see how small details have been clarified, as well as adjustments in brightness and contrast.

Summary

Nano-photonic technology has great potential for use in applications that will lead to improved communication

systems and computers. It can also serve to break down the current "resolution barrier" that limits the accuracy of images achieved through microscopy and imaging devices used in medicine and security. ❖



Professor Zeev Zalevsky, of the School of Engineering at Bar-Ilan University, is a noted expert in optical super resolution, fiber optical devices, photon embedded silicon chip devices, microwave photonics, three-dimensional mapping and light beam shaping. He has published two books, as well as over 180 articles in leading international periodicals and journals. He has also registered over 15 patents. Prof. Zalevsky holds a BSc and a doctorate (PhD) in electrical engineering from Tel Aviv University.

Meir Shragay is a senior research engineer – and a veteran of Israel Aerospace Industries.

For additional reading:

Z. Zalevsky, "Integrated micro and nano photonic dynamic devices: A review," J. of Nano Photonics 01(01), 012504 (2007).

Z. Zalevsky, "Photon transistors in Silicon" Technologies, 306, 192-196 (February 2007).

D. Mendlovic, Z. Zalevsky and A. W. Lohmann, "Various approaches in super resolution," Optics and Photonics News, 8, 21-22 (1997).

V. Mico, J. Garcia and Z. Zalevsky, "Optical imaging resolves beyond the diffraction limit," Laser Focus World, 97-1