Dielectric Gratings Come into Focus

Sub-wavelength dielectric grating mirrors with non-periodic patterning show focusing abilities

Researchers at Hewlett-Packard Laboratories, Palo Alto, have developed flat dielectric grating mirrors that focus infrared light. The sub-wavelength gratings have a non-periodic design that allows controlling the phase fronts of the reflected light waves. Depending on their patterning the planar reflectors can focus the light like a cylindrical or a spherical mirror.

As David Fattal and his colleagues report, the grating mirrors were made from a 450 nm amorphous silicon layer on a quartz substrate. The silicon layer was patterned by plasma-enhanced chemical vapour deposition and dry etching. First the researchers prepared a periodic grating with parallel silicon grooves and a period of 760 nm. This grating had high reflectivity in a broad spectral region from 1.4 µm to 1.9 µm. In addition the phase of the reflected light varied nearly by 2 π across this spectral region.

Since the wavelength of the reflected light was much larger than the period of the grating, the light experienced a surface with smoothed-out dielectric properties. This gave rise to a continuous rescaling: One could vary the phase of the reflected light not only by changing the wavelength but also by changing the period of the grating for a fixed wavelength. This rescaling was experimentally confirmed by the HP-team. When light with 1.55 µm wavelength was reflected from various gratings with periods between 0.4 µm and 1.4 µm, the phase varied roughly from 0 to 2 π.

By locally changing the pitch of a grating one could therefore sculpture the phase properties of a reflected light beam. By giving the beam a parabolic phase profile one could focus the beam, with a focal length proportional to the curvature radius of the phase profile. Numerical simulations corroborated this. A grating with the proper modulation of the local period could change the phase of a 20 µm wide light beam from center to edge by 8 π, giving it a parabolic profile and leading to focusing. The reflectance remained high at about 98 %.

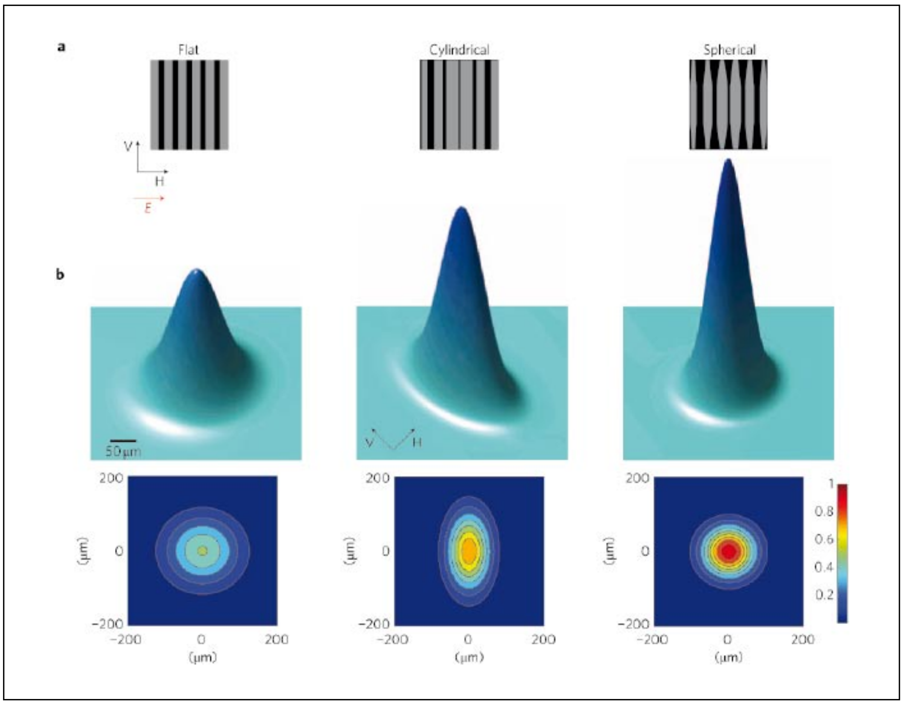

FIGURE: **flat (left), cylindrical (middle) and spherical (right) sub-wavelength grating mirrors. The red arrow indicates the intended polarization of the incident light. (b) Measured beam profiles at the foci for the three mirrors.** (Courtesy of David Fattal et al., Nature Photonics)

Finally the researchers fabricated several non-periodic grating reflectors with aperture radii of 150 µm. For theses gratings the periods were kept fixed but the width of the silicon grooves was spatially modulated in one or two directions. Modulation in one direction resulted in grooves of different width, modulation in the other direction lead to a width changing along each groove.

These modulations had the same effect on the phase of the reflected light as a corresponding modulation of the grating period. The non-periodic grating mirrors focused a reflected light beam in one or two directions like a cylindrical or a spherical mirror, respectively, with a focal length of 20 mm. Imperfections of the grooves lead to a reduced reflectivity of 80 to 90 %, which was much lower than the expected 98 %. But the researchers are confident that a higher reflectivity can be reached by improving the fabrication process.

The non-periodic grating mirrors could have many interesting applications, as the researchers point out. These cheap and compact mirrors could laterally confine light in a VCSEL cavity, shape the transverse mode profile of a microlaser, replace expensive lens systems in DVD players or digital cameras, or they could be used instead of microlens arrays in CCD sensors.

Rainer Scharf

Further information:

- David Fattal et al.: Flat dielectric grating reflectors with focusing abilities. Nature Photonics, (published online: May 2nd, 2010) http://dx.doi.org/10.1038/nphoton.2010.116
- Quantum Science Research at Hewlett-Packard Laboratories, Palo Alto: www.hpl.hp.com/research/qsr
- David Fattal: www.stanford.edu/~dfattal

Steering the Beam of a Microlaser

A photonic-crystal structure allows for on-chip control of the laser beam direction

Many applications of semiconductor lasers would benefit from an on-chip control of the beam direction – instead of using complicated mechanical systems and mirrors to deflect the beam. Researchers at Kyoto University have taken a big step towards this goal. They fabricated a composite photonic-crystal structure with artificial band edges that made it possible to continuously change the beam direction of an adjacent semiconductor laser.

Susumu Noda and his colleagues made a two-dimensional photonic crystal with triangular holes that were arranged in an unusual way. Some holes formed a square lattice whereas others were arranged in a rectangular lattice, which had one lattice constant fixed and the other slowly changing along one axis of the photonic crystal. This composite structure gave rise to artificial band edges in the band structure of the photonic crystal. Since the crystal was slowly modulated along one axis, the artificial band edges had a position-dependent wave vector δk different from 0.

At each band edge the group velocity of light vanished and the crystal supported a cavity mode. A planar semiconductor laser, which was beneath the photonic crystal, could couple resonantly to one of these cavity modes if the in-plane wave vector of a laser mode and the wave vector δk of a cavity mode matched. In this case the photonic crystal emitted laser radiation with a nonzero in-plane wave vector. The emission direction was shifted by an angle arcsin($\delta k/k_0$) from the normal direction, where k_0 was the wave number of the emitted radiation.

Since the wave vector of the band edges changed continuously along the photonic crystal, the researchers only had to excite the active layer of the laser at the right position to get emission in the desired direction. To achieve this they gave the semiconductor laser a p-electrode, which consisted of 30-40 parallel segments, each $17\times50\ \mu m^2$ large and separated by a 3 µm wide gap, sitting on top of the photonic crystal. The bottom n-electrode consisted of a single element. The typical pump current required for lasing was 100 mA.

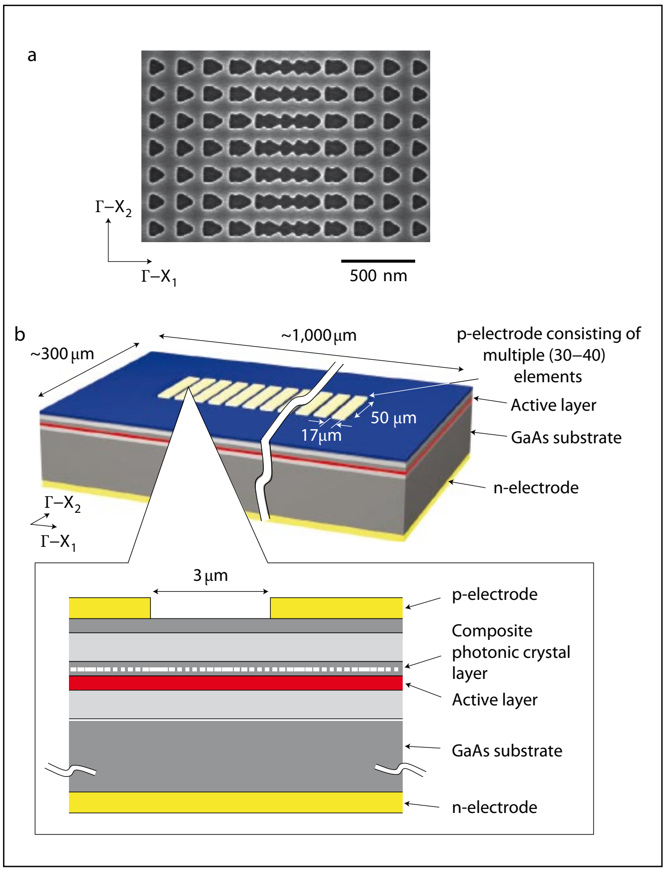

FIGURE: **Composite photonic crystal and device structure. (a) Scanning microscope image of a portion of the fabricated composite photonic crystal. (b) Device structure containing the photonic crystal.** (Courtesy of Yoshitaka Kurosaka et al., Nature Photonics)

When only two neighboring elements of the p-electrode were used to excite the laser, light was emitted along the k-vector that fit to the δk of the “local” band edge. By selecting the element pairs that excited the laser, the emission direction could be changed over a range of 30° in steps of 1°. The researchers could also change the emission direction continuously by exciting the laser with a triple of neighboring elements of the p-electrode. They let different currents flow through the electrode elements and slowly shifted the relative strengths of the currents. This continuously changed the wave vector δk of the lasing band edge and thereby smoothly varied the emission angle of the laser beam. The wavelength of the laser remained constant at 970 nm.

As the researchers point out, controlling the current injection in the laser electrodes by an integrated electronic circuit could lead to advanced control of the laser beam or even to simultaneous and multi-directional emission. They anticipate a wide-reaching effect on many applications like ultra-compact mobile-laser displays, chip-to-chip optical communication, laser-radar sensing systems and even medical laser knives.

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Further information:

- Yoshitaka Kurosaka et al.: On-chip beam-steering photonic-crystal lasers. Nature Photonics (published online: May 2nd, 2010) http://dx.doi.org/10.1038/nphoton.2010.118
- Susum Noda at Kyoto University: www.kuee.kyoto-u.ac.jp/~lab05/index_e.html
- Eiji Miyai et al.: Lasers producing tailored beams. Nature 441, 946 (2006) http://dx.doi.org/10.1038/441946a

Miniaturized 3D Worlds

New 3D patterning technique creates nanoscale structures

Scientists from IBM Research have created nanoscale structures with a new technique that uses a tiny, silicon tip with a sharp apex. The tool – which can sit on a tabletop – promises capabilities at very high resolutions, reduced cost and complexity. The patterning technique opens new prospects for developing nanosized objects in fields such as electronics, future chip technology, medicine, life sciences, and opto-electronics.

To demonstrate the technique's capability, the team created recognizable 3D patterns using different materials for each. One example is the 25 nanometer high 3D replica of the Matterhorn, the Swiss mountain that soars 4,478 m high. It was created in molecular glass, representing a scale of 1:5 billion (one nanometer in the vertical pattern corresponds to 57 altitude meters).

One further example is a complete 3D map of the world measuring only 22 by 11 micrometers. At this size 1000 world maps could fit on a grain of salt, assuming 0.3 mm as the average size of a grain of salt. The map was "written" – on a polymer called polyphthalaldehyde. In the relief, one thousand meters of altitude correspond to roughly eight nanometers. It is composed of 500,000 pixels, each measuring 20 nm^2 and was created in only 2 minutes and 23 seconds.

The tiny, very sharp silicon tip – measuring 500 nanometers in length and only a few nanometers at its apex – is attached to a bendable cantilever that controllably scans the surface of the substrate material with the accuracy of one nanometer. By applying heat and force, the nano-sized tip can remove substrate material based on predefined patterns – operating like a "nanomilling" machine with ultra-high precision. By modulating the force or by readdressing individual spots, more material can be removed: To create the 3D-replica of the Matterhorn, for example, 120 individual layers of material were removed from the molecular glass substrate. Furthermore, there is the ability to assess the pattern directly by using the same tip to create an image of the written structures.

The two materials used are similar to substrate materials used in conventional nanofabrication techniques. The molecular glass consists of snow-flake-like molecules, measuring about one nanometer with an almost spherical shape. At a tip temperature above 330 °C, the hydrogen bonds that hold the molecules together break, allowing the molecular parts to become mobile and to escape from the surface.

Potential applications of the technique range from fast prototyping for CMOS nanoelectronics to creating prototype optical components and meta-materials, from fabricating 3D nano-particles to shape-matching templates for the self-assembly of nanoscale objects such as nano-rods or nano-tubes.

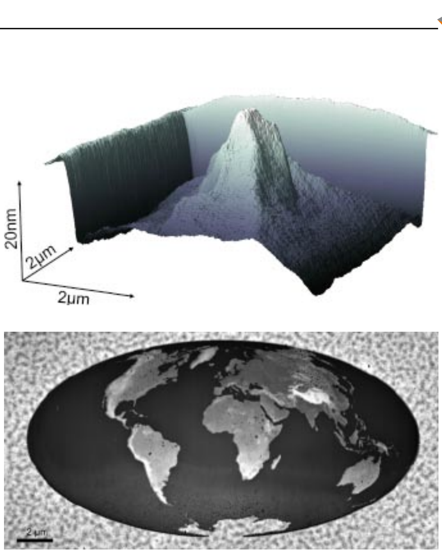

FIGURE: **25 nanometer high 3D replica of the Matterhorn and 3D map of the world measuring 22 by 11 micrometers.** (Courtesy of IBM Research – Zurich)

IBM Research/KP

Further information:

- IBM Research - Zurich: www.zurich.ibm.com
- D. Pires, J. L. Hedrick, A. De Silva, J. Frommer, B. Gotsmann, H. Wolf, M. Despont, U. Duerig, A. W. Knoll: Nanoscale 3D patterning of molecular resists by scanning probes. Science Express (April 22nd, 2010)
- A. Knoll, D. Pires, O. Coulembier, P. Dubois, J. L. Hedrick, J. Frommer, U. Duerig: Probe-based 3-D Nanolithography using Self-Amplified Depolymerization Polymers. Advanced Materials, Advanced Online Publication (April 22nd, 2010)

Video-rate STED

Nanoscopy of living neurons

Light microscopy is the most popular imaging method in the biological sciences. In particular, studying dynamics opened up an enormous field of application. Meanwhile the diffraction barrier has been overcome by a number of nanoscopy or super-resolution techniques, like Stimulated Emission Depletion (STED) microscopy, invented by the team of Stefan W. Hell. Hell and his colleagues from the Max Planck Institute for Biophysical Chemistry and the European Neuroscience Institute, Göttingen, Germany are working to adapt the technology to video-rate STED microscopy of living cell constituents.

In a recent publication the researchers draw a direct comparison of conventional and high-resolution movies from inside living cells using confocal and pulsed mode STED microscopy. Studying synaptic vesicles within a living axon, a lateral resolution of 65 nm could be observed in STED movies at video rates (28 frames per second), which is 4-fold higher in spatial resolution than in confocal microscopy. Whereas confocal microscopy could only reproduce the axon, the STED movies clearly visualized the motion of single vesicles, revealing specific patterns of movement within the confined space of the axon. Furthermore, the team demonstrated that video-rate STED microscopy can also be performed with continuous wave beams, allowing for capturing more photons per unit time. This could facilitate extending fast STED imaging towards imaging fainter living samples.

www.biophotonics-journal.org

Further information:

M. A. Lauterbach, J. Keller, A. Schönle, D. Kamin, V. Westphal, S. O. Rizzoli, S. W. Hell: Comparing video-rate STED nanoscopy and confocal microscopy of living neurons. Journal of Biophotonics (published online: April 8th, 2010), DOI: 10.1002/jbio.201000038