

A tabletop waveguide delivers coherent x rays

The layered anode emits bright, directed beams without the need for mirrors or large-scale accelerators.

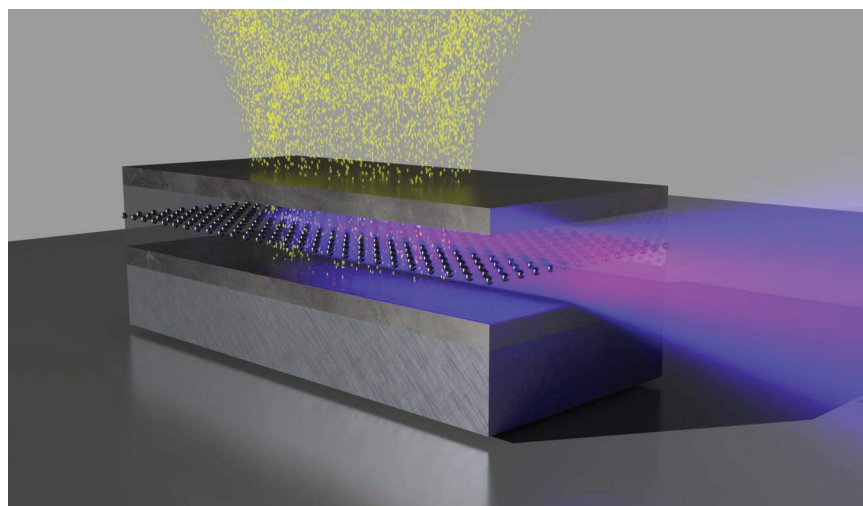
Tools for imaging the interior of solid objects have come a long way since Wilhelm Röntgen accidentally discovered x rays and captured an image of his wife's hand bones in 1895. Röntgen would likely be amazed by today's synchrotron light sources, in which coherent beams of x rays scattered by an object can be used to reconstruct nanoscale structures such as crystals and biological macromolecules.

Bright beams of x rays that are emitted in a single direction onto the target of interest are difficult to come by in a laboratory setting. Unlike large-scale accelerators, which emit highly collimated beams, small-scale laboratory sources generate x rays in all directions. Once they're emitted, x rays may be concentrated or redirected with mirrors, crystals, and lenses. However, collecting photons over a wide angular range and refocusing them onto a sample is hampered because, for x rays, the difference between the index of refraction of any two materials is tiny. Furthermore, filtering out incoherent light to improve the beam's coherence also has the detrimental effect of reducing the flux.

Malte Vassholz and Tim Salditt of the University of Göttingen have now developed and demonstrated an approach for generating coherent x-ray radiation directly within a waveguide structure.¹ The layered material that makes up the waveguide, depicted in an artist's impression in figure 1, emits x rays within a nanometers-wide channel. The resulting beam's brilliance—that is, the number of photons of a given wavelength and direction that are concentrated on a spot per unit time—exceeds that of a conventional x-ray tube by two to three orders of magnitude.

Seeking brilliance

The basic method by which laboratory-scale sources produce x rays is similar to the technique first used by Röntgen. Electrons, accelerated by a high voltage and focused into a beam microns in diameter, collide with a metal anode in a sealed vacuum tube. Radiation is emitted



at all angles when the atoms in the metal deflect and slow those electrons and when the electrons excite the atoms.

One early way to boost brilliance was to swap out the stationary anode with a rotating one. Because the heat from the electron beam is dispersed evenly across the anode surface, the anode can tolerate higher beam current and power, and as a result can produce x rays with higher flux and energy, which depends on the acceleration voltage of the electrons. By the 1950s rotating anode tubes had become the standard design for diagnostic x-ray imaging.

The next major improvement in x-ray brilliance came in 2003, when researchers at Sweden's Royal Institute of Technology in Stockholm developed anodes based on jets of liquid metal.² In those setups, the anode is continuously regenerated by a stream of molten metal. That development offered an order-of-magnitude increase in brilliance over conventional x-ray tubes and enabled analytical applications, including phase-contrast imaging and high-resolution diffraction. Those sources have since become common tools for providing the 10 keV x rays, desirable for high-contrast imaging work.³

Today the brightest and most coherent known sources of x rays are synchrotrons and x-ray free electron lasers. (See the article by Phil Bucksbaum and Nora Berrah, *PHYSICS TODAY*, July 2015, page 26.) Those building-sized relativistic light sources emit radiation with brilliance more than 10 orders of magnitude

FIGURE 1. METAL ATOMS in a thin film become excited and generate x rays (purple) when electrons (yellow) bombard a layered waveguide structure (gray) in this artist's impression. The x rays emerge from the end of the structure in a beam of spatially coherent light. (Courtesy of University of Göttingen/Julius Hilbig.)

greater than conventional x-ray tubes. When coupled into suitable waveguides, for example, the radiation can form a coherent beam that enables not just traditional x-ray and phase-contrast imaging but also tomography on nanoscale materials including liquids, single crystals, and thin films.

Salditt and his research group rely on x-ray imaging techniques to probe the structure of biological tissues. The researchers have carried out holographic imaging at synchrotron radiation sources and have performed phase-contrast tomography using in-house x-ray sources. "We could never quite bring the tomography in the lab to the resolution range necessary to resolve the structure of individual cells in the tissues," says Salditt. The sequential approach of first generating x rays and then coupling them to a waveguide to provide coherence is unsuited for low-brilliance laboratory x-ray sources: There simply aren't enough photons. But Salditt's familiarity with waveguide optics gave him an idea.

Layered solution

To harness the filtering power of a waveguide to improve the brilliance of a lab-

oratory source, Salditt and his graduate student Vassholz proposed generating the x rays inside the waveguide itself. As illustrated in figure 2a, waveguiding becomes possible for x rays by total reflection within suitable thin-film structures or in two-dimensional channels.⁴

Vassholz and Salditt built a 5-mm-long sandwich-like structure made up of an iron or cobalt metal sheet embedded between guiding and cladding layers. A high-energy (15 kV to 50 kV) electron beam was generated by an instrument adapted from a microfocus x-ray tube. The beam excited the central metal layer, causing it to emit x rays that were funneled into the guiding layers.

The radiation propagated within the 10 nm channels of the guiding layers, and spatially coherent light was emitted either through the top of the waveguide at an angle, as shown in figure 2b—in the case of a leaky design based on a thin top cladding layer—or out the open end of the waveguide. The former produced a 100 μm source spot with small divergence; the latter, a smaller source spot with high divergence. Both emissions can be useful for different applications and adjusted by varying the layer thickness.

A silicon drift detector placed across from the waveguide exit showed sharp peaks in emission intensity as a function of spatial position. The peaks corresponded to the waveguide modes and indicated that the device had effectively channeled x rays onto a target. From the photon counts recorded under conditions of a low current that would not saturate the detector, the researchers extrapolated that the source could reach a brilliance of up to 10^{11} photons/(s mrad² mm²) when fully powered. That value corresponds to an improvement over conventional sources of two orders of magnitude. “It’s not really difficult to build, once you know how it should be designed. It’s just that no one thought that changing from a bulk anode to a waveguide structure would make any difference,” says Salditt.

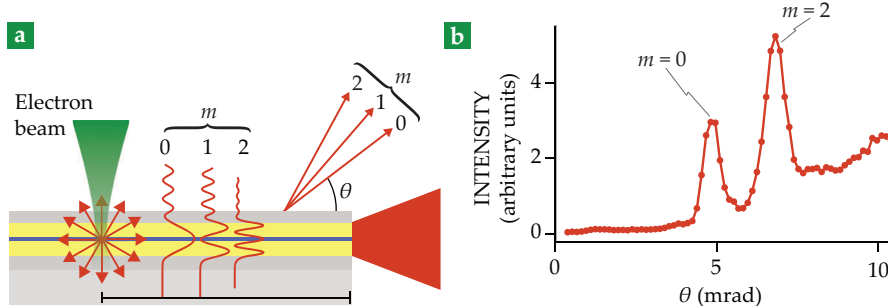


FIGURE 2. X-RAY GENERATION in waveguides produces spatially coherent light. **(a)** An electron beam (green) impinges upon a planar waveguide consisting of cladding (gray) and guiding (yellow) layers and a central fluorescent metal layer (blue). The electron impact excites metal atoms, which directly emit x rays (red arrows) into waveguide modes (red wavy lines) with mode numbers m . The x rays exit the channel through the cladding at angle θ with respect to the waveguide or out the end. **(b)** Detected far-field emission of the x rays that leave through the top of the waveguide at angle θ shows sharp peaks corresponding to the waveguide modes, m . (Adapted from ref. 1.)

Additional experiments and calculations suggested that the brilliance of the emitted x rays could be further increased—by up to several additional orders of magnitude—by using different metals or by varying the thickness of the layers. According to simulations and experiments, the distance between the spot of electron impact and the waveguide exit can be used to control the far-field emission pattern.

New directions

The improved coherence of x-ray radiation within a resonant cavity is an example of the quantum electrodynamic Purcell effect, in which a system’s spontaneous emission rate—in this case, of x rays—can be enhanced by its environment. Achieving the effect in a tabletop waveguide allows a glimpse of nanoscale structures that could otherwise only be seen with diffraction imaging that uses visible light lasers and with x rays in synchrotron experiments.

Claudio Pellegrini of Stanford University observes that the technique is similar to a much older proposal that uses channeling in a crystal to obtain x-ray emission in a well-defined direction instead of the full solid angle. But for the crystal, the

channel size is a few angstroms and thus can only be used for extremely narrow-band radiation.⁵ The waveguide’s larger channel size of 10 nm offers a resonant-cavity approach that can be used with standard electron sources.

The new waveguide-based design could enable benchtop measurements of nanoscale structures that until now have only been accessible using large-scale instruments. Changing from a planar to a channeled waveguide could provide a beam that is both coherent and directed in two lateral dimensions—ideal for holographic imaging experiments, for example. Says Vassholz, “We’re driven by imaging tools, but the possibilities are really open-ended with the new design’s degree of freedom.”

Rachel Berkowitz

References

1. M. Vassholz, T. Salditt, *Sci. Adv.* **7**, eabd5677 (2021).
2. O. Hemberg, M. Otendal, H. M. Herz, *Appl. Phys. Lett.* **83**, 1483 (2003).
3. M. Otendal et al., *Rev. Sci. Instrum.* **79**, 016102 (2008).
4. S. P. Krüger et al., *J. Synchrotron. Radiat.* **19**, 227 (2012).
5. S.-L. Chang et al., *Phys. Rev. Lett.* **94**, 174801 (2005). PT



From Tight Spaces to Tight Tolerances

we machine sapphire,
ceramics, quartz & glass

www.insaco.com
215.536.3500



Earning your
trust since 1947

