Gamma-ray waveguides

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(Received 18 January 2008; accepted 13 March 2008; published online 15 April 2008)

We have developed an approach for gamma-ray optics using layered structures acting as planar waveguides. Experiments demonstrating channeling of 122 keV gamma rays in two prototype waveguides validate the feasibility of this technology. Gamma-ray waveguides allow one to control the direction of radiation up to a few MeV. The waveguides are conceptually similar to polycapillary optics, but can function at higher gamma-ray energies. Optics comprised of these waveguides will be able to collect radiation from small solid angles or concentrate radiation into small area detectors. Gamma-ray waveguides may find applications in medical imaging and treatment, astrophysics, and homeland security. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2905280]

Presently, there are limited methods for focusing or concentrating medium-energy gamma rays. At energies above ~100 keV, one is limited to using collimators, masks, and Bragg optics.[1,2] While Bragg/Laue concentrating optics have promise for large astronomical observatories (some possibly using multiple space vehicles), their usefulness for other applications is limited due to required large focal lengths, often exceeding 10 m.[3,4] Here, we describe a new approach to gamma-ray optics based on channeling in waveguides made from multilayered structures consisting of alternating thin-film layers of a high-density reflecting material and a low-density spacer material. These structures can act as planar waveguides for gamma rays with energies between ~100 keV and a few MeV. We report channeling of 122 keV gamma rays in flat and curved waveguide structures composed of a high-density gold-palladium alloy film and a low-density polymer film. These results establish the feasibility of using gamma-ray waveguides to construct concentrating optics with potentially important applications in medical treatment and diagnostics, astrophysics, materials research, and for monitoring and detecting nuclear materials.

Reflective x-ray and gamma-ray optics are based on total external reflection that is possible because at these photon energies denser materials generally have lower refractive indices than less dense materials or vacuum. For high-energy photons, the refractive index is related to the electron density in the material N_e by $n \approx [1-(\omega_p/\omega)]^{1/2}$, where ω is the photon frequency and ω_p is the plasma frequency, $\omega_p = (4\pi N_e e^2/m)^{1/2}$, and m and e are the electron mass and charge, respectively.[5] High-energy radiation in a medium of low density ρ_1 impinging on denser material of density ρ_2 at small grazing angle θ totally reflects if the grazing angle is less than a critical angle; i.e., $\theta < \theta_c \approx (\omega_{p2}^2 - \omega_{p1}^2)^{1/2}/\omega \approx 6 \times 10^{-5}[(\rho_2-\rho_1)/10\ \mathrm{g\ cm^{-3}}]^{1/2}[E/1\ \mathrm{MeV}]^{-1}$, where E is the photon energy.[5] For x-rays of a few keV the critical angle is ~0.01 rad, which is large enough to permit the fabrication of extremely effective reflecting telescopes[6,7] and capillary optics for concentrating radiation.[8,9] Reflective optics have been tuned to work well at energies up to ~100 keV by using special multilayer coatings.[10,11] However, at energies above 100 keV, these approaches are ineffective because of the difficulties of constructing reflecting surfaces of the needed smoothness and alignment and because the focal distances become excessively large. Bragg/Laue crystal optics potentially could overcome some of these problems,[12] but typically they also require large focal lengths.

Here, we describe experimental results that demonstrate gamma-ray channeling using carefully constructed waveguides and propose that such structures can be used to extend high-energy optics up to a few MeV with relatively short focal distances. Planar gamma-ray waveguides are multilayer structures with alternating thin layers of low-density and high-density materials. These devices channel gamma rays whose incident grazing angle θ_I is less than the critical angle θ_c. Gamma rays propagate through the low-density material with relatively little attenuation while repeatedly reflecting from the high-density layers. By curving the waveguides, one can design short-focal-length systems that can concentrate gamma rays to small spots or can capture gamma-ray emission from a small solid angle.[13] This waveguide approach has several advantages over traditional reflective optics or Bragg/Laue optics. Because the gamma rays are reflected multiple times in the waveguide, the total angular deflection can be much larger than can be realized using other approaches. These large deflections enable one to design optical systems with much shorter focal distances. Additionally, the waveguides can concentrate gamma rays over a broad energy band. They are limited at low energies by attenuation in the low-density material and at high energies by a decrease in the critical angle. A set of curved waveguides that deflect gamma rays by differing angles can be aligned to concentrate gamma rays to a line.[13] Inserting a second set of waveguides orthogonal to the first can bring the radiation to a small spot. Using this approach, which is analogous to that used in a Kirkpatrick–Baez optic,[14] one can design gamma-ray optics with short (~1 m) focal lengths.

By collecting radiation from a small solid angle, the channeling optics can create a high-resolution image by scanning or by using multiple concentrators with an array focusing to a position sensitive detector. Concentrating radiation into a small area reduces the background signal, allowing for higher signal to noise measurements in shorter times.

The critical question about this new approach to gamma-ray optics is whether it is indeed possible to construct multilayer waveguide structures with the needed tolerances

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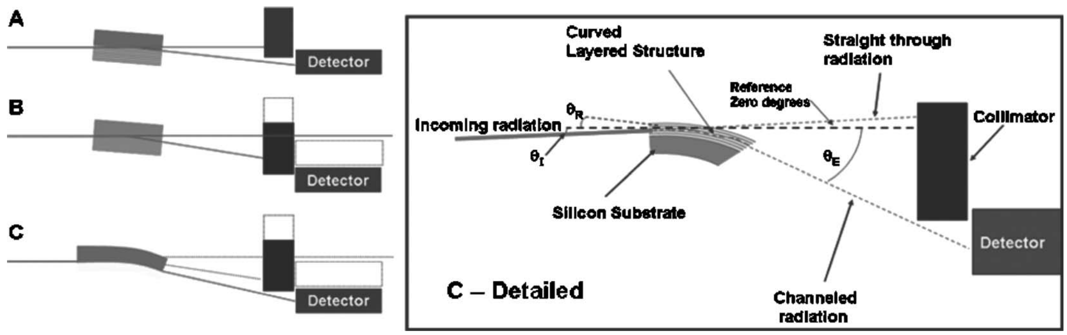

FIG. 1. Schematic of the experimental setup for measuring channeled radiation in curved structures. Channeling in a straight structure is verified using an offset detector and collimator as shown in (a). The detector and collimator are then moved to block the straight-channeled radiation (b). Finally, the sample is curved and radiation is detected in the offset detector (c). The right inset shows a larger diagram of the experimental configuration (c) with the angles defined: θ_R is the angle of rotation of the sample θ_I is the angle if incidence of the radiation onto the layers, and θ_E is the angle of the emerging radiation.

in dimensions and smoothness to efficiently channel gamma rays. To demonstrate channeling, we fabricated two 4 cm by 3 cm thin-film multilayer structures on silicon substrates. One consists of ten alternating layers of 40 nm thick sputter-deposited Au–Pd and 4 μm thick spin-coated UV curable polymer film. A second similar structure consists of 30 pairs of gold-palladium layers and 1.2 μm thick polymer layers. The Au–Pd layers serve as reflectors while the low-density polymer keeps the Au–Pd layers separated, smooth, and parallel. The acceptance angle of the waveguide, or its numerical aperture, is $\theta_c = 5.5 \times 10^{-4}$ rad or 0.031°.

We measured the gamma-ray-waveguiding properties of the multilayer structures with the setup schematically shown in Fig. 1. Two 38 cm long steel plates with a 45 μm $\times 25$ mm gap between them collimated the radiation from a ^{57}Co source (122 keV). The emerging knife beam of radiation is collimated to $\sim 2.5 \times 10^{-4}$ rad, i.e., $\sim 0.5\theta_c$. The gamma rays strike the edge of the multilayer waveguide that is mounted on a high-precision motorized rotation stage. A second collimator with a relatively large 8 mm gap attaches to a $15 \times 15 \times 7.5$ mm^3 coplanar grid cadmium zinc telluride (CZT) detector mounted on a manual translation stage allowing alignment of the detector and source. The CZT detector's energy resolution of $<10\%$ counts only the photons in the 110–140 keV range, thereby reducing most of the background radiation.

For gamma rays that are channeled in a flat waveguide, approximately half are deflected $\sim 2\theta_I$, where θ_I is the grazing angle between the incident beam and the layers of the structure, and the other half move in the incident direction (see Fig. 1). To verify that the gamma rays are channeled in the waveguide structure, we initially move the detector and collimator so that one side of the collimator blocks radiation propagating in the incident direction (only one side of the detector collimator is shown in the figure for clarity). As the flat waveguide rotates [Fig. 1(a)], the incident radiation is deflected by up to $2\theta_c$ and the CZT detector measures the transmitted radiation. These measurements confirm channeling in the flat waveguide structure.

In a curved waveguide the gamma rays can be deflected up to $\sim 2\theta_c$ per reflection. To see the effects of multiple reflections, we move the detector and collimator so that they block the deflected radiation from the flat waveguide [Fig. 1(b)]. The waveguide was then curved so that the emerging 122 keV radiation is deflected beyond what is possible for the flat structure [Fig. 1(c)]. The detection of radiation that is deflected by more than $2\theta_c$ verifies gamma-ray channeling in the curved waveguides.

Figure 2 displays the results of our experiments. The straight waveguide channeling data (diamond shaped points) were taken with the experiment in the configuration shown in Fig. 1(b). These data represent the background, as there is no deflected radiation entering the detector. Then, we curved the waveguide as shown in Fig. 1(c), so that the deflected radiation enters the detector as the curved waveguide is rotated (plane crosses). At rotation angle $\theta_R = 0$, the entrance to the curved waveguide is coaligned with the gamma-ray beam and the maximum radiation is channeled past the collimator into the detector. As θ_R approaches $\pm\theta_c$, channeling becomes less effective leading to a diminished count rate. We repeatedly moved the collimator to block the radiation and then increased the curvature of the waveguide to deflect the gamma ray around the collimator. Using this procedure maximum deflections of $5.8\theta_c$ in the first waveguide (4 μm thick polymer) and $6.3\theta_c$ in second waveguide (1.2 μm thick polymer) were measured. When the waveguides were curved further, the radiation leaked out of the structure and was not effectively channeled. At the maximum deflection of each waveguide, the fraction of the incident gamma rays that is

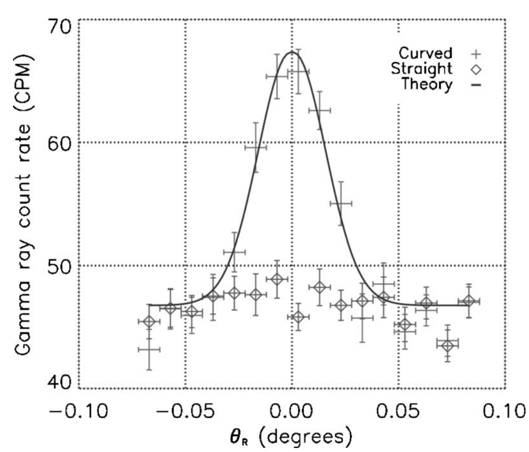

FIG. 2. Measurements of gamma-ray channeling. The peak in the gamma-ray count rate at rotation angle θ_R of the curved waveguide (cross symbols) is evidence that the gamma rays are channeled and deflected. The vertical error bars represent relative errors of $n^{1/2}$, where n is the total number of points in a given bin (there are ~23,000 counts in this dataset). Horizontal error bars give the binning of the data. The solid curve is the theoretical fit to the channeling peak using the waveguide roughness and the width of the incoming beam as the only free parameters.

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transmitted is 5% and 10%, for the first and second waveguide, respectively. The losses are largely due to absorption and Compton scattering in the polymer and scattering caused by the surface roughness of the Au–Pd layers. Both types of losses can be mitigated in future waveguides. By making the low-density layer thinner, the same curvature can be attained in a shorter, less absorbing waveguide. Furthermore, using more advanced growth techniques that yield subnanometer roughness can reduce scattering losses.

The solid curve in Fig. 2 is a theoretical model fit that includes effects of the width of the incoming beam, attenuation in the polymer, silicon, and collimator, geometry of the curved waveguide, and reflection losses due to the roughness of the metal layers.[15] Channeled gamma rays will be reflected $N(\theta_I) \sim L|\theta_I|/s$ times before exiting the waveguide, where $L=4$ cm is the length of the waveguide structure and s is the thickness of the polymer layers. The average attenuation of the channeled radiation due to reflection losses is $A_{\mathrm{ref}}=R^N$, where R is the reflectivity. The static Debye–Waller estimate of the reflectivity is $R(\theta_I)=R_F(\theta_I)\exp(-4k^2\theta_I^2\sigma^2)$, where $R_F(\theta_I)$ is the Fresnel reflectivity for a smooth surface, k is the photon wave number, and σ is the rms surface roughness. The expected channeling peak, $C(\theta_R)$ (solid curve in Fig. 2), is obtained by convolving A_{ref}, the output beam from the first collimator $I(\theta_R)$, and the blockage from the collimator in front of the detector, i.e.,

$$C(\theta_R) = \eta \int d\theta_I I(\theta_I) A_{\mathrm{ref}}(\theta_I) f(\theta_E).$$

The factor $\eta < 1$ allows for the partial acceptance of the incident gamma-ray beam by the waveguide due to alignment. The incident beam is measured to have an approximately Gaussian shape with a width of 125 μm at the entrance to the waveguide and an angular spread of 2.5×10^{-4} rad. The factor $f(\theta_E)$ accounts for the attenuation in the final steel collimator at the detector for radiation that emerges at angle θ_E.

The best fit of the function $C(\theta_R)$ to the channeling peak data in Fig. 2 is obtained with $\sigma=1.5$ nm. Direct measurements of the roughness of the top surface of the multilayer structure with an atomic force microscope (AFM) give an rms roughness of 3 nm. For high energy radiation the actual reflectivity is higher than the static Debye–Waller estimate we used, possibly due to lateral correlation of the roughness profile.[15,16] Therefore, the inferred value of σ is not inconsistent with the direct AFM measurement. The surface reflectivity for gamma rays is largely independent of energy. Near the critical angle the reflectivity depends on $k\theta_c\sigma \sim \omega_{p2}\sigma/c$, which is independent of photon energy. Above a few MeV, the effectiveness of the waveguides diminishes because of the increasing importance of Compton scattering in the polymers.

The results presented here demonstrate that gamma rays with energies above 100 keV can be efficiently channeled in multilayer waveguides fabricated using conventional techniques. Gamma-ray waveguides could enable improved methods for medical imaging radiation therapy, astrophysical measurements, and nuclear material detection.

The authors gratefully acknowledge support from the LDRD and IGPP programs at LANL and from the DOE NA-22 RD Program Office and from the DHS DNDO.

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