X-ray beam compression by tapered waveguides
H.-Y. Chen (陳心誼), S. Hoffmann, and T. Salditt

Citation: Appl. Phys. Lett. 106, 194105 (2015);
View online: https://doi.org/10.1063/1.4921095
View Table of Contents: http://aip.scitation.org/toc/apl/106/19
Published by the American Institute of Physics

Articles you may be interested in
High aspect ratio x-ray waveguide channels fabricated by e-beam lithography and wafer bonding
Journal of Applied Physics 115, 214305 (2014); 10.1063/1.4881495

Hard x-ray nanoprobe based on refractive x-ray lenses
Applied Physics Letters 87, 124103 (2005); 10.1063/1.2053350

Invited Article: A unified evaluation of iterative projection algorithms for phase retrieval
Review of Scientific Instruments 78, 011301 (2007); 10.1063/1.2403783

Focusing hard x rays beyond the critical angle of total reflection by adiabatically focusing lenses
Applied Physics Letters 110, 101103 (2017); 10.1063/1.4977882
X-ray beam compression by tapered waveguides

H.-Y. Chen (陳心誼), a) S. Hoffmann, and T. Salditt b)
Institut für Röntgenphysik, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

(Received 6 February 2015; accepted 2 May 2015; published online 12 May 2015)

We have fabricated linear tapered waveguide channels filled with air and imbedded in silicon for the hard x-ray regime, using a processing scheme involving e-beam lithography, reactive ion etching, and wafer bonding. Beam compression in such channels is demonstrated by coupling a pre-focused undulator beam into the channels, and recording the exit flux and far-field diffraction patterns. We achieved a compressed beam with a spot size of 16.48 nm (horizontal) × 14.6 nm (vertical) near the waveguide exit plane, as determined from the reconstructed near-field distribution, at an exit flux which is eight times higher than that of an equivalent straight channel. Simulations indicate that this gain could reach three to four orders of magnitude for longer channels with tapering in two directions. © 2015 AIP Publishing LLC.

X-ray waveguides (WGs) can be used to generate quasi-point sources for hard x-ray imaging. These kinds of x-ray optics have first been realized as planar layered systems [one-dimensional waveguide (1DWG)], and later also as two-dimensional confined channels (2DWGs), as required for applications in coherent imaging. In contrast to most other nano-focusing optics such as Kirkpatrick-Baez (KB) mirrors, Fresnel zone plates (FZP), or compound diffractive lenses, 2DWGs deliver nanoscale x-ray beams with controllable spatial coherence. The quasi-point source of the WG exit emits smooth wavefronts which are ideally suited for holographic imaging. At the same time, the absorption in the cladding assures extremely low background illumination, without contributions from higher diffraction orders as in FZP focusing or the pronounced tails of KB-optics. Hence, they also enable nanoscale diffraction studies at significantly reduced background. In addition to spatial and coherence filtering, WGs can also concentrate the beam, based on geometric tapering. For present imaging applications, WGs without beam compression are used and have to be combined with high gain pre-focusing optics to reach the flux needed for imaging applications. In a state of the art realization of this scheme, a KB-beam of about 200–300 nm cross-section was coupled into WGs with an exit size of d = 50–70 nm, delivering a flux in the range 109–109 ph/s. The smallest WG beam diameters down to 10 nm have been achieved by crossing two high transmission 1DWGs slices to form an effective 2DWG. This crossed 2DWG system is limited, however, for reasons of its intrinsic astigmatism, as well as the absorption in the carbon guiding layer of the WGs, which becomes important for lower photon energy. Furthermore, the planar thin film fabrication technology is not compatible with variations in shape function. To overcome these limits, we have developed an alternative fabrication scheme based on e-beam lithography, reactive ion etching, and wafer bonding, which gives buried air or vacuum channels in silicon.

In this work, we use this fabrication approach to realize WGs with a taper function, which concentrate and filter the beam at the same time. This can either be used to match the entrance width D to the pre-focusing optics and to funnel more photons to a smaller exit width d, or in future extensions to make pre-focusing optics in front of the WG obsolete, at least for some applications. An earlier experimental realization of a tapered waveguide (tWG) was demonstrated by an air-gap 1DWG, while tapered 2DWG is addressed in this work. To demonstrate the concept of tWG beam compression in lithographically defined channels, we couple an undulator beam focused by KB-mirrors to 300 nm into a tWG and guide it further to d ≃ 75 nm at the exit.

For the design of the present experiment, we have used finite difference simulations (FDSs) to study the beam propagation in tWGs, based on the parabolic wave equation. In addition, the propagation in x-ray WGs with straight channels has been studied previously, showing that beam compression and filtering can be combined in a tWG. Both Bergemann et al. and Kukhl et al. have studied linearly tapered x-ray WGs or capillaries by analytical and numerical calculations, addressing the minimum beam width at the exit; while Panknin et al. have also included non-linear tapering profiles and Bukreeva et al. have studied corrugated WGs.

Fig. 1(a) shows the wave optical simulation of guided wave propagation in a one-dimensional linear tWG (vacuum in silicon), as obtained by FDSs. The WG length L = 5 mm was chosen for all WGs to ensure sufficient absorption of radiative modes at the given photon energy E = 13.8 keV, with a calculated transmission T = 5.25 × 10−7, correspondingly assuring an extremely low background signal. The slope of the WG interface and the associated linear tapering geometry are limited by the critical angle of total internal reflection θc ≃ 2θc ≃ 2.25 mrad corresponding to the index of refraction nsi = 1 − δ + iβ, with δ = 2.554 × 10−6 and β = 2.047 × 10−4, and guiding layer with ncl = 1. In the example shown in Fig. 1(a), the entrance and exit sizes of the WG are D = 334 nm and d = 73 nm, and the taper angle θ = 26 μrad. The simulation illustrates the rapid decay

a)Electronic addresses: hchen2@gwdg.de and tsaldit@gwdg.de

0003-6951/2015/106(19)/194105/4/$30.00 106, 194105-1 © 2015 AIP Publishing LLC
of the wave intensity in bulk silicon and the much weaker absorption in the tapered guiding layer. With \( \psi(x, z) \) denoting the field inside the WG and \( \psi_0 \) the incident plane wave, the intensity enhancement can be defined as the maximum of the normalized intensity \( I_{\text{max}} = \max \left\{ \frac{|\psi(x, z)|^2}{|\psi_0|^2} \right\} \), where \( I_{\text{max}} = 11 \) for the simulated WG in Fig. 1(a). This enhancement appears towards the end of the WG as a maximum with a flux density one order of magnitude higher than at the WG entrance. In this manner, beam compression by the tWG is clearly evidenced. In order to demonstrate this concept experimentally, we have fabricated a WG chip with many parallel tWGs, and finally diced to \( L = 5 \text{ mm} \). The optical characterization of the WGs was performed at the GINIX (Göttingen Instrument for Nano-Imaging with X-rays) at the P10 beamline at the PETRA III synchrotron facility in Hamburg (DESY). Fig. 1(b) shows a schematic of the experimental setup, along with electron micrographs of the entrance and exit plane of a representative WG (labeled as “C” below). The WG entrance had a width of 334 nm and a depth of 69 nm; the WG exit had a width of 73 nm and a depth of 51 nm. The WG entrance was aligned in the focal plane of the KB-mirror system. The far-field images were recorded by a single photon counting pixel detector (Pilatus 300 K, Dectris) with \( 172 \times 172 \mu m^2 \) pixel size, placed 5.1 mm behind the WG. For 13.8 keV, a KB-flux of \( I_{\text{KB}} = 7.32 \times 10^{10} \) photons/s was recorded, and a focal spot size of 295 nm (FWHM) in horizontal and 181 nm (FWHM) in vertical direction, respectively. The far-field intensity distribution of the WG labeled “C” is shown in Fig. 1(c), with \( 2.79 \times 10^{10} \) photons/s impinging onto its entrance, for a 1 s accumulation. The flux at the exit was measured to \( I_{\text{WG}} = 2.69 \times 10^8 \) photons/s. Next, the angular acceptance \( \omega \) of the WG, defined as the width (FWHM, Gaussian fit) of the exit intensity as a function of angle of incidence, was determined by rotating the WG around the \( y \)-axis by an angle \( x \) and measuring the integrated far-field intensity, as shown as solid squares in Fig. 1(d). In addition, numerical simulations for WGs of different taper angles \( \theta \), labeled by A, B, and D with \( \theta = 55, 31, \) and 10.2 \( \mu \text{rad} \), respectively, are depicted by lines. Label “S” stands for a straight channel reference. Both curves are normalized to the maximum intensity and are in very good agreement. As shown in Fig. 1(e), the angular acceptance decreases with the taper angle \( \omega(\theta) \) as expected from wave optical simulations (Table I). In a geometric optical framework, this is explained by the increase in the number of reflections \( n \) and in particular, by the correspondingly increasing internal reflection angles \( \theta_n \) at the interfaces between guiding layer and cladding, see also the sketch in Fig. 3(b). The beam can only be guided in the \( z \)-direction, as long as the internal angle is smaller than the critical angle \( \theta_n \leq \theta_c \), else it is absorbed in the cladding.

A precise analysis of the beam confinement due to the WG geometry is obtained by reconstructing the complex wave field using the measured far-field intensities in the near-field regime right behind the WG exit using the error reduction (ER) algorithm. The reconstructed near-field intensity distribution and the corresponding reconstruction of the far-field pattern are shown in Fig. 2. As usual in iterative phase retrieval methods, the “reconstructed far-field” is computed from the reconstructed near-field intensity and can be tested against the measured far-field (see Fig. 1(c)), in order to check consistency and convergence of the phase retrieval process. The ER algorithm was initialized with the auto-correlation of the near-field, obtained by an inverse Fourier transform of the recorded far-field data, shown in Fig. 1(c). The support constraint was implemented using a Gaussian function with a width (FWHM) eight times larger than the size of the WG exit, in the respective direction. Fig. 2(a) shows the reconstructed far-field intensity pattern of a tWG (“C”) on logarithmic scale, which is found in very good agreement with the measured data, as shown in Fig. 1(c). Figs. 2(b) and 2(c) show intensity and phase of the reconstructed near-field image in the WG exit plane. Gaussian fits to the central peak of the near-field intensity along the principal directions are shown in Figs. 2(d) and 2(e), respectively. They indicate an effective

| Table I. Entrance and exit size of the guiding layer, with the corresponding taper angle \( \theta \), and the angular acceptance \( \omega \) for the tWGs labeled as “A,” “B,” “C,” and “D” along with a straight reference channel “S.” |
|-----------------|---|---|---|---|---|
| WG label       | A | B | C | D | S |
| \( D \) (nm)    | 686 \times 67 | 478 \times 65 | 334 \times 69 | 180 \times 70 | 74 \times 70 |
| \( d \) (nm)    | 136 \times 63 | 166 \times 65 | 73 \times 51 | 78 \times 50 | 75 \times 50 |
| \( \theta/\theta_c \) | 0.0244 | 0.0137 | 0.0116 | 0.0045 | \( < 4 \times 10^{-3} \) |
| \( \omega/\omega_c \) | 0.511 | 0.675 | ... | 0.875 | 1.187 |
The WG and the intensity exiting the WG is calculated using the ratio of the intensity impinging onto the WG defined as the ratio of the intensity of the tWG over the straight reference WG channel roughness and internal defects. The gain $G$, defined as the ratio of the intensity of the tWG over the straight reference, is calculated by

$$G_{\text{Sim}} = \frac{\int_{\text{WG}} |\psi(x, z = L)|^2 \, dx}{\int_{\text{WG}} |\psi(x, z = 0)|^2 \, dx} \quad \text{and} \quad G_{\text{Exp}} = \frac{I_{\text{WG}} \times A_{KB}}{I_{KB} \times A_{WG}} ,$$

yielding to $G_{\text{Sim}} = 8.05$ for the numerical simulation, and $G_{\text{Exp}} = 6.89$ for the experiment. This demonstrates clearly that a linear tWG can efficiently compress the beam, even if real structure effects such as roughness and waviness deteriorate the experimental values for $T$. In fact, after obtaining the results shown in Figs. 1 and 2, further improvements in the fabrication protocol regarding, in particular, wafer bonding under inert gas and changes in the exposure protocol were implemented and led to significantly better controlled channel side walls, and correspondingly higher $T$ as detailed in elsewhere.\textsuperscript{27}

In order to further optimize tWGs in view of $I_{\text{max}}$, the entrance width can be enlarged to collect more photons from the incoming beam, while the exit width can be tailored to the favored size and divergence for a specific experiment. In this way, the improved WG imaging could even be implemented without high gain focusing optics, such as the present KB-system. Fig. 3(a) illustrates the intensity enhancement $I_{\text{max}}$ as a function of the taper angle $\theta$, achieved by compressing a beam to an exit size of $d = 10 \text{ nm}$ over a channel length $L = 2.4 \text{ mm}$, simulated for vacuum in Si at $E = 11 \text{ keV}$. We chose $d = 10 \text{ nm}$ in view of holographic imaging experiments which require a small source size. The $I_{\text{max}}(\theta)$ curve first steeply increases, as more photons are collected, but reaches a maximum at $\theta_{\text{max}} = 0.124\theta_c$, before declining again, when the internal reflection angle increases above the critical angle $\theta_n \geq \theta_c$ towards the end of the channel, see (b). For illustration, we trace a ray for $\theta_{\text{max}}$, shown as a red line in (b). From $\theta_n = (2n - 1)\theta_c \leq \theta_c$, we can infer that the channel supports $n = 4$ internal reflections.\textsuperscript{27} For higher numbers of reflections $n \geq 5$, $\theta_n \geq \theta_c$ lead to a leaking into the cladding material, see blue arrow in (b). However, a fraction of the x-ray beam is still reflected and guided inside the tWG (red arrow). The

| WG label | $I_{\text{WG}}$(cps) | $T_{\text{Exp}}$(%) | $T_{\text{Sim}}$(%) | $w_x$ (nm) | $w_y$ (nm) |
|----------|---------------------|---------------------|---------------------|-------------|-------------|
| C        | $2.69 \times 10^8$  | 0.96                | 8.9                 | 16.48       | 14.60       |
| S        | $3.34 \times 10^7$  | 0.47                | 5.9                 | 16.95       | 14.13       |

for the simulation $T_{\text{Sim}}$ and the experiment $T_{\text{Exp}}$, where $A_{WG}$ and $A_{KB}$ are the cross section areas of the WG entrance and the KB beam size. The measured flux of the tWG ("C") is $I_{\text{WG}}^C = 2.69 \times 10^8 \text{ cps}$ and of the straight reference WG ("S") $I_{\text{WG}}^S = 3.34 \times 10^7 \text{ cps}$. The simulated transmission $T_{\text{Sim}} = 8.9\%$ of the tWG is 9.27 times higher than the experimental transmission $T_{\text{Exp}} = 0.96\%$, which is affected by channel roughness and internal defects. The gain $G$, defined as the ratio of the intensity of the tWG over the straight reference, is calculated by $G_{\text{Sim}} = \int_{\text{WG}} |\psi(x, z = L)|^2 \, dx \quad \text{and} \quad G_{\text{Exp}} = \frac{I_{\text{WG}}^C}{I_{\text{WG}}^S} ,$

| FIG. 2. Results of the reconstruction by the ER algorithm. (a) Reconstructed far-field image of the tWG (labeled as “C”), using logarithmic scale. Scale bar: 5 nm. (b) Intensity (logarithmic scale) and (c) phase (in radian) of reconstructed near-field distribution, obtained after 1500 ER iterations. Scale bar: 40 nm. (d) and (e) Gaussian fits to two perpendicular profiles of the central peak, along x- and y-axis. |

| FIG. 3. FDS of a tWG in Si for $d = 10 \text{ nm}$, $L = 2.4 \text{ mm}$, and $E = 11 \text{ keV}$ ($\theta_c = 2.84 \text{ mrad}$). (a) The curve $L_{\text{inc}}(\theta)$ has a maximum at $\theta_{\text{max}} = 0.124\theta_c$. (b) For the given parameters, the channel supports 4 internal reflections, before leakage is observed at $\theta > \theta_c$. (c) and (d) Sketch of the linear taper geometry with taper in (c) one and (d) two dimensions. (e) and (f) Wave propagation inside a (e) one- and (f) two-dimensional tWG, with intensity plotted on logarithmic scale. |

TABLE II. Comparison of a representative tWG channel “C” and a straight channel “S,” selected for an identical exit aperture of about $70 \times 50 \text{ nm}$, and recorded under identical settings of the KB-focused beam. The total WG intensity, the corresponding experimental transmission value $T_{\text{Exp}}$, along with the numerically predicted values $T_{\text{Sim}}$, and beam spot size in the WG exit plane, $w_{x/y}$ (FWHM) are shown.
gray dashed line in (b), (e), and (f) indicates the position where the fifth reflection occurs, corresponding to a tWG beam with width of 16.34 nm. This is in good agreement with the visual inspection of the leakage based on the logarithmically scaled intensity distribution, see (e) and (f). Despite the fact that the reflected angle exceeds the critical angle towards the end of the channel, the WG still reaches $I_{\text{max}} = 66.7$, underlining the substantial compression. For the same parameters, but in a two-dimensional taper geometry, the simulation yields $I_{\text{max}} = 4206$, as shown in (f).

In summary, tWGs have been designed based on FDSs, fabricated and characterized by experiments with synchrotron radiation. A pre-focused monochromatic x-ray beam was coupled into the front side of a TWG with an entrance width matching the focal spot size. The beam coupled into the WG was further compressed by propagation in the guiding channel with linear taper, resulting in a gain of about one order of magnitude over a straight channel waveguide. Simulations for a two-dimensional cone geometry indicate that gain values $G \approx 10^4$ could be reached by a WG tapered in two dimensions, given future improvements in realizing tapered profiles in both directions orthogonal to the optical axis.

We thank Mike Kanbach for helping WG fabrication, Anna-Lena Robisch for phase retrieval, and Michael Sprung for the support for the P10 beamline. We gratefully acknowledge the German Research Foundation (DFG) for funding through Grant No. SFB 755/C1, and appreciate the financial support from the Ministry of Science and Technology of China (NSC 102-2917-I-564-062).

1M. Bartels, M. Krenkel, J. Haber, R. Wilke, and T. Salditt, Phys. Rev. Lett. 114, 048103 (2015).
2E. Spiller and A. Segmüller, Appl. Phys. Lett. 24, 60 (1974).
3Y. P. Feng, S. K. Sinha, H. W. Deckman, J. B. Hastings, and D. P. Siddons, Phys. Rev. Lett. 71, 537 (1993).
4S. Di Fonzo, W. Jark, S. Lagomarsino, C. Giannini, L. De Caro, A. Cedola, and M. Müller, Nature 403, 638 (2000).
5W. Jark, A. Cedola, S. Di Fonzo, M. Fiordelisi, S. Lagomarsino, N. V. Kovalenko, and V. A. Chernov, Appl. Phys. Lett. 78, 1192 (2001).
6F. Pfeiffer, C. David, M. Burghammer, C. Rickel, and T. Salditt, Science 292, 1230 (2001).
7A. Jarre, C. Fuhse, C. Ollinger, J. Seeger, R. Tucoulou, and T. Salditt, Phys. Rev. Lett. 94, 074801 (2005).
8P. Kirkpatrick and A. V. Baez, J. Opt. Soc. Am. 38, 766 (1948).
9O. Hignette, P. Cloetens, W.-K. Lee, W. Ludwig, and G. Rostaing, J. Phys. IV France 104, 231 (2003).
10H. Mimura, S. Matsuyama, H. Yumoto, H. Harai, K. Yamamura, Y. Sano, M. Shibahara, K. Endo, Y. Mori, Y. Nishino et al., Jpn. J. Appl. Phys., Part 2 44, L539 (2005).
11S. Matsuyama, H. Mimura, H. Yumoto, Y. Sano, K. Yamamura, M. Yabashi, Y. Nishino, K. Tamasaku, T. Ishikawa, and K. Yamauchi, Rev. Sci. Instrum. 77, 103102 (2006).
12W. Chao, B. D. Harteneck, J. A. Liddle, E. H. Anderson, and D. T. Attwood, Nature 435, 1210 (2005).
13C. G. Schroer and B. Lengeler, Phys. Rev. Lett. 94, 054802 (2005).
14M. Müller, M. Burghammer, D. Flot, C. Rickel, C. Morawe, B. Murphy, and A. Cedola, J. Appl. Cryst. 33, 1231 (2000).
15C. Krywka, H. Neubauer, M. Priebe, T. Salditt, J. Keckes, A. Buffet, S. V. Roth, R. Doehrmann, and M. Müller, J. Appl. Cryst. 45, 85 (2012).
16M. J. Zwanenburg, J. H. H. Bongaerts, J. F. Peters, D. Riese, and J. F. van der Veen, Physica B 283, 285 (2000).
17I. Bukreeva, D. Pelliccia, A. Cedola, F. Scarinci, M. Ilie, C. Giannini, L. De Caro, and S. Lagomarsino, J. Synchrotron Radiat. 17, 61 (2010).
18S. P. Krüger, H. Neubauer, M. Bartels, S. Kalbfleisch, K. Giewekemeyer, P. J. Wilbrandt, M. Sprung, and T. Salditt, J. Synchrotron Radiat. 19, 227 (2012).
19H. Neubauer, S. Hoffmann, M. Kanbach, K. Giewekemeyer, S. Kalbfleisch, S. Krüger, and T. Salditt, J. Appl. Phys. 115, 214305 (2014).
20M. J. Zwanenburg, J. F. Peters, J. H. H. Bongaerts, S. A. de Vries, D. L. Abernathy, and J. F. van der Veen, Phys. Rev. Lett. 82, 1696 (1999).
21C. Fuhse and T. Salditt, Appl. Opt. 45, 4603 (2006).
22L. De Caro, C. Giannini, S. Di Fonzo, W. Yark, A. Cedola, and S. Lagomarsino, Opt. Commun. 217, 31 (2003).
23S. Panknin, A. Hartmann, and T. Salditt, Opt. Commun. 281, 2779 (2008).
24C. Bergemann, H. Keymeulen, and J. F. van der Veen, Phys. Rev. Lett. 91, 204801 (2003).
25S. V. Kukhlevsky, F. Flora, A. Mariani, G. Nyitray, Zs. Kozma, A. Ritucci, L. Palladino, A. Reale, and G. Tomassetti, X-Ray Spectrom. 29, 354 (2000).
26I. Bukreeva, A. Popov, D. Pelliccia, A. Cedola, S. B. Dabagov, and S. Lagomarsino, Phys. Rev. Lett. 97, 184801 (2006).
27See supplementary material at http://dx.doi.org/10.1063/1.4921095 for details about fabrication and characterization of tapered X-ray waveguides.