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Design optimization of a periodic microstructured array anode for hard X-ray grating interferometry

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Abstract

Talbot-Lau grating interferometer (TLGI) has great advantages in X-ray imaging contrasts, especially for low-Z materials, over conventional absorption contrast. A microstructured array anode target (MAAT) source offers significantly higher imaging throughput than the combination of an extended X-ray source paired with an absorption grating (also known as source grating). The performance of the MAAT source can be optimized with respect to the areal density, dimensions, and choice of material for the microstructured metal inserts (MMI) and the substrate in which they are embedded. In this paper, we analyze the X-ray generation efficiency per incident electron, relative fraction of X-rays generated by MMI and substrate, X-ray spectrum, and angular distribution via Monte Carlo simulation. Based on the simulation results, the optimal parameters are obtained for a MAAT with incident electron energies from 30 keV to 120 keV. The corresponding temperature distribution within the MAAT is also simulated for the optimal set of the parameters via finite element analysis. As demonstrated by the thermal analysis data, the maximum allowable electron-beam power loading was derived that allows a stable operation of the transmission MAAT.

Keywords

Talbot-Lau grating interferometer; X-ray imaging; microstructured array anode target; Monte Carlo simulation

1. Introduction

X-ray radiology and computed tomography (CT) based on absorption are among the most widely used diagnostic tools in application fields such as industrial inspection, security screening and medical diagnosis. However, if weakly absorbing samples (Low-Z materials)

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are under investigation with high energy the absorption contrast is extremely low and the applicability of conventional absorption X-ray imaging is limited. Recently, X-ray phase contrast imaging (XPCI) has attracted more attention due to its increased sensitivity for imaging weakly absorbing low-Z materials (Lewis 2004, Momose 2005, Bech *et al* 2009, Bravin *et al* 2013). For low Z materials, X-ray phase contrast is more than three orders of magnitude ($>1000\times$) larger than absorption contrast at X-ray energies greater than 20 keV, and increases with increasing X-ray energy (Momose and Fukuda 1995, Momose 2005).

Several XPCI methods have been developed during the past few decades. Among them, Talbot-Lau grating interferometer (TLGI) (Pfeiffer *et al* 2006) has shown great potential for practical applications because it can provide three contrast modes simultaneously: a phase contrast image related to the real part of the refractive index in a material, an absorption contrast image like that obtained in a conventional X-ray imaging system, and a dark field image that is determined to small-angle X-ray scattering at structures typically below the spatial resolution of the imaging setup (sub-pixel) (Yaroshenko *et al* 2014). Those images provide complementary and comprehensive information about the object (Pfeiffer *et al* 2008, Bech *et al* 2010, Bech *et al* 2013, Michel *et al* 2013). Indeed, a wide range of applications demonstrated enhanced performances, including pre-clinical lung disease investigation (Scherer *et al* 2017), breast cancer imaging and the diagnosis (Willner *et al* 2014, Wang *et al* 2015, Li *et al* 2018) and monitoring of early stage osteoarthritis (Stutman *et al* 2011).

A major advantage of TLGI is the ability to use a high power, low brilliance X-ray source to perform phase contrast imaging with high throughput. An absorption grating G0 must be placed in front of the source to generate the required degree of spatial coherence, however this has several significant drawbacks. First, as a result of preventing more than 50% of the X-rays from illuminating the specimen it reduces the effective source brilliance by this same amount. Second, the grating lines of the G0 need to be sufficiently opaque to X-rays. With the current state of microfabrication of high aspect ratio structures this requirement is achievable with X-rays below 20 keV so that they absorb over 95% of the X-rays, it becomes more difficult for X-ray energies above 20 keV. The limited penetration of 20 keV X-rays are insufficient for imaging anything thicker than human fingers or small animals. Existing designs for 35–80 keV X-rays that are typically used in clinical applications have been demonstrated to substantially reduce radiation dose to patients (e.g. breast cancer CT (Zhao *et al* 2012)) using synchrotron-based Talbot XPCI. However, the special design for this energy range suffers from some limitations such as measuring a single row of pixels at a time (Thüring *et al* 2014).

The aspect ratio (AR) of gratings is defined as $AR = h/w_0$, where h is the structure height ($h \propto E_x^3$ for an absorption grating, where E_x denotes the X-ray energy), which was limited by the fabrication process, usually X-ray lithography (Mohr *et al* 2012) or photolithography (David *et al* 2002); w_0 is the opening width of the grating. The structure height of a gold G0 grating required to absorb 95% of X-rays is $20\mu\text{m}$ at 20 keV, but rapidly increases to $350\mu\text{m}$ at 60 keV. With a $1\mu\text{m}$ opening width of the G0 grating, the AR increases from 20 : 1 at 20 keV to 350 : 1 at 60 keV. Currently, the best grating manufacturing capability can achieve AR up to 50 : 1 for $1\mu\text{m}$ line width gold gratings (Li *et al* 2018).

A small opening width of the G0 is required to ensure that the spatial coherence length at phase grating G1 is comparable or preferably larger than the period of the G1. The spatial coherence length of an X-ray beam is approximately given by $\xi = R\lambda/w_0$, where R denotes the distance between the source and phase gratings, λ the wavelength of the X-rays, and w_0 the opening width of the G0. It is clear that making a viable G0 at 35–80 keV is a formidable task and a critical bottleneck for the TLGI. In addition, absorption gratings with high aspect ratio effectively collimate the beam and as a result limit the field of view (FOV) of a TLGI interferometer. For a TLGI imaging setup with a source-to-sample distance of L_s , the maximum available FOV is given by $FOV = 2L_s/AR$ (Thüring *et al* 2011). The FOV is just 1 cm when a source-to-sample distance of $L_s = 250\text{ mm}$ and an aspect ratio of $AR = 50$. Even though bent gratings can be adopted to eliminate the limitation of the AR of gratings, the large area and high AR bent grating are more difficult to fabricate (Thüring *et al* 2011). Increasing the G0 opening will decrease the spatial coherence length which must be compensated by increasing the distance between the source and G1 grating, which will increase the overall length of the interferometer. The detected X-ray flux which is inversely proportional to the square of the distance between source and detector would be substantially reduced by increasing the G0 opening.

The G0 and its associated limitations may be eliminated entirely using a microstructured source, effectively combining the source and G0 into a single element. Many approaches to implementing a structured X-ray source have been proposed and developed. One method involves fabricating grooves on a rotating anode but this approach limits the interferometer to a small FOV because the coherence is different on the different target position (Momose *et al* 2009, Du *et al* 2011). A photo emitter X-ray source array composed of a laser light source and a photo cathode electron source was proposed, but the system is extremely complicated (Hesselink *et al* 2014). Takayoshi Shimura *et al.* have successfully demonstrated how a microstructured array anode target (MAAT) can be used effectively to develop a compact TLGI within a 1 m source-detector distance (Shimura *et al* 2013). Morimoto *et al.* have experimentally shown a compact TLGI with a single transmission grating combined with a MAAT source (Morimoto *et al* 2014, Morimoto *et al* 2015a, Morimoto *et al* 2015b). However, its power (60 W) and the working energy (20 kV) are too low to image a large sample quickly. Sigray (Concord, USA) has developed and commercialized a MAAT X-ray source with X-ray power over 400 W (Yun *et al* 2015).

In this paper, the key parameters of MAAT source are investigated and optimized for TLGI applications for a broad range of incident electron energies from 30 keV to 120 keV using Monte Carlo simulation.

2. Materials and methods

The goal when designing a MAAT source is to maximize X-ray production in the microstructured metal inserts (MMI) and minimize it in the substrate material. In order to maximize X-ray production in the MMI, candidate materials are selected that have high atomic number, high mass density, high thermal conductivity, and high melting point. Diamond is the preferred substrate material because it has outstanding thermal conductivity, low mass density, and low atomic number.

A typical transmission MAAT consisting of an array of micron-sized high Z and high mass density element, e.g., W, Mo, and Cu, embedded in a low Z and low mass density substrate, is shown in figure 1.

When an X-ray target material is bombarded by energetic electrons, the rate of bremsstrahlung production is generally expressed by the mass radiation stopping power S_{rad} (in $MeV\ cm^2\ g^{-1}$) (Podgoršak 2010)

$$S_{rad} = B_{rad} \alpha r_e^2 Z^2 \frac{N_A}{A} E_e \quad (1)$$

where B_{rad} is equal to 16/3 for electron in the non-relativistic energy range, α denotes the fine structure constant, r_e the classical electron radius, Z the atomic number of the target material, N_A Avogadro constant, A Atomic mass number, and E_e the initial total energy of the electron.

According to equation (1), a large ratio of mass density and atomic number of MMI to diamond leads to a large ratio of X-ray production in the MMIs to the diamond substrate, resulting in favorable spatial X-ray production profile (distribution) in the target. With tungsten as the MMI material and diamond as the substrate, more than 90% of X-rays are produced in the tungsten microstructures while less than 10% are produced in the diamond. Therefore, the microstructured array anode target source is equivalent to a G0 grating with 90% absorption placed in front of an extended X-ray source. Morimoto et al. have demonstrated that TLGI produces high visibility fringes using a MAAT source in an experiment that realized a compact interferometer without the need for any inefficient absorption grating (Morimoto *et al* 2014, Morimoto *et al* 2015b, Morimoto *et al* 2015a).

Important performance parameters of the MAAT X-ray source for TLGI include X-ray production efficiency per incident electron, intensity ratio and spatial distribution of the X-rays generated by the MMIs and the substrate, X-ray source brightness, and spatial distribution of electron beam power load. These parameters are dependent on the shape, dimension, and material of the MMIs and the substrate material, electron beam spot size, and incident electron energy.

X-ray production efficiency per incident electron (B) is an important parameter that characterizes the performance of a transmission MAAT source, which is defined as the number of photons emitted per unit area and unit solid angle per incident electron (Ihsan *et al* 2007),

$$B = \frac{I_0}{N_e \cdot \Delta S \cdot \Delta \Omega} \quad (2)$$

where I_0 is the number of photons emitted from the focal spot, N_e is the number of electrons simulated, Ω is the solid angle, S is the effective focal size of X-rays. An X-ray energy threshold of one-third of the accelerating voltage was used in the simulations to remove the effects of beam hardening.

Monte Carlo (MC) type simulations are a well-known method to create a simulacrum of the electron and matter interactions that can be used to calculate many parameters of interest including the production of X-rays in an MAAT. In this work a well-established MC simulation software, Geant4, was used to calculate the X-ray production efficiency per incident electron, spatial distribution of X-rays produced in the microstructured target, angular distribution of X-ray beam intensity with respect to the target surface normal, and the energy deposition ratio in the MAAT. Using the energy deposition ratio, the temperature distribution inside the MAAT was simulated for a given electron beam profile using SOLIDWORKS Simulation Professional (Waltham, MA), a commercial finite element analysis program. The temperature distribution is useful to optimize operating conditions of the MAAT. Based on this simulation, the maximum electron beam power loading on the MAAT was determined.

Geant4 is freely available MC simulation tool-kit and developed by CERN (Agostinelli *et al* 2003). With object-oriented flexibility, all kinds of interactions of particles with matter for a wide range of energies are described by a set of comprehensive physics models, thus it can precisely model the electromagnetic interactions of electrons, photons, ions and hadrons with matter down to very low energy (eV scale). Two low energy electromagnetic models are specially optimized for low energy particles: Penelope (Salvat *et al* 2008) and Livermore (based on the Livermore library (Cullen *et al* 1997, Perkins, Cullen & Seltzer 1991, Perkins, Cullen, Chen, Rathkopf, Scofield & Hubbell 1991)). Both libraries have shown very good agreement with other databases, but a lower intensity of the characteristic tungsten lines in Livermore model was showed compared to the bremsstrahlung slope (Guthoff *et al* 2012, Pandola *et al* 2015), so that the Penelope physical model was adopted in our simulation.

For our study, the size of microstructured area composed on one-dimensional MMI lines is $210.0\mu\text{m} \times 210.0\mu\text{m}$, the period of MMI lines is $3.0\mu\text{m}$ and the width is $1.0\mu\text{m}$ (33.3% duty cycle). The simulated detector has a 20.0mm diameter and is positioned at 50.0mm from the MAAT electron incidence entrance surface along the electron incidence direction (y-axis in figure 1). An X-ray energy threshold of one-third of the electron acceleration voltage was implemented in Geant4 using an energy cutoff as opposed to a physical barrier to expedite the simulations. The detector is assumed to have 100% detection efficiency for X-rays of energy larger than energy threshold. The cut-in-range which limits the production of secondary photons and electrons was set to $0.01\mu\text{m}$, which is much smaller than the thickness of the MMIs. 10^{10} mono-energetic electrons were emitted within a diameter of $100.0\mu\text{m}$ from the electron gun which are uniformly distributed across the center of the MAAT with an energy corresponding to the peak voltage for each simulation.

3. Optimization of the parameters of MAAT

The dimension of the MMIs and substrate are critically important to the production of the X-rays within the MAAT and also the degree to which they attenuated upon X-ray intensity to the detector. For the MAAT considered here, the width and the length of the MMIs are fixed leaving the thickness as the only free parameter of the MMI to be determined. When the thickness of MMIs as smaller than the average penetration depth of the incident electrons the interaction of the incident electrons with the MMIs will be limited, resulting inefficient

production of X-rays by the incident electrons. On the other hand, when the thickness is much larger than the electron penetration depth, self-absorption can become significant. To optimize the thickness of the MMIs, the X-ray production efficiency was maximized as a function of thickness. In the following simulation we investigate three candidate materials for use as MMI structures: tungsten (W-MMI), molybdenum (Mo-MMI), and copper (Cu-MMI). Four electron energies are considered, 30 keV, 60 keV, 90 keV and 120 keV. The thickness of the diamond substrate is $300.0\mu\text{m}$.

Figure 2 presents the X-ray production efficiency as a function of the thickness of MMI for three MMI materials at four electron energies. B-Spline interpolation was used to interpolate data between the calculated points in the curves. The results show that X-ray production efficiency initially increases with increasing thickness due to greater probability of interaction between the incident electrons and the MMIs. A maximum is obtained for the MMI thickness when further increases in interaction are offset by self-absorption within the MMI. Further increases in thickness lead to decreasing the X-ray production efficiency as attenuation increases. Note that three MMI materials show the same trend as a function of the thickness. These results indicate the importance of optimizing the size of the MMIs to achieve higher brightness.

The optimized thickness of MMI increases with the increasing electron energy, similar trend to the average path length of electrons as a function of electron energy. Figure 3(a–c) show the optimal thickness of MMI (black line) and average path length of electrons (blue line) (Berger 2005) of W, Mo, Cu as a function of electron energies ranging from 30 keV to 120 keV. For a 30 keV electron beam energy, the optimal thicknesses are $2.0\mu\text{m}$, $3.3\mu\text{m}$ and $3.5\mu\text{m}$ for W-MMI, Mo-MMI and Cu-MMI. It is interesting to note those optimal thicknesses are comparable to the corresponding average electron path length of electrons of $2.2\mu\text{m}$ (W), $3.2\mu\text{m}$ (Mo) and $3.3\mu\text{m}$ (Cu), respectively. The simulation was performed at four electron energies, 30, 60, 90, and 120 keV. The curve from 30 to 120 keV is obtained by fitting a curve using the simulated results at the four energies. As expected, the optimal thickness increases with electron energy. A linear model was used for fitting the simulated data because the rate of bremsstrahlung production is proportion to the initial total energy of electron according to equation (1). The fitting results were added in the figure 3 (a–c). The optimal thickness of W-MMI is smaller than that of Mo-MMI and Cu-MMI because W has a larger atomic number(Z). Figure 3(d) shows the X-ray production efficiency of three transmission MAATs with optimized thickness of MMI as a function of electron beam energy. Compared with the single microstructured anode target (SMAT) proposed by Ihsan (Ihsan *et al* 2009, Zhou *et al* 2016), the optimal thickness of transmission W-MMI becomes larger. For instance, at the electron energy 90 keV, the optimal thickness of transmission W-MMI is $15.0\mu\text{m}$, while the optimal thickness of SMAT is less than $5.0\mu\text{m}$. Optimal thickness of W-MMI increases as a consequence of electron multiple scattering. Scattering between incident electrons and the atoms of the target material occurs frequently, and due to the difference in average path length of electrons between diamond and MMI, scattering between neighboring microstructures is possible.

Figure 4 shows the X-ray production profile of optimal thickness of W-MMI, Mo-MMI and Cu-MMI at 90 keV incident electron energy with 10^9 per simulation. The relative fraction of

X-rays generated by W-MMI, Mo-MMI and Cu-MMI are defined as the ratio $R_i = (I_{i-MMI} - I_{Diamond}) / (I_{i-MMI} + I_{Diamond}) \times 100\%$, where i stands for W, Mo and Cu, I_{i-MMI} stands for average X-rays produced in MMI of one period, $I_{Diamond}$ stands for average X-rays produced in diamond of one period. Based on the simulation result, R_{W-MMI} , R_{Mo-MMI} , R_{Cu-MMI} are 96.3%, 90.3%, 85.1% respectively.

In addition to supporting the MMI structures, the diamond substrate of the MAAT source can double as the X-ray source vacuum window. The substrate attenuates X-rays generated in the MMIs and impacts the overall X-ray intensity of the MAAT source. For a substrate material of linear absorption coefficient (μ) and thickness (L), the transmittance (T) of X-rays passing through a material is given by

$$T = e^{-\mu L} = e^{-L/L_{1/e}} \quad (3)$$

$L_{1/e}$ denotes attenuation length (the length through which the intensity of an X-ray beam of a specific energy will be reduced by a factor of $1/e$). Generally speaking, the attenuation length scales inversely to the atomic number of the material. Therefore, a lower atomic number is highly preferred,

$$L_{1/e} \propto \frac{E_x^3}{Z^4} \quad (4)$$

Where E_x denotes the X-ray energy in keV and Z means the atomic number. The figure 5(a) presents the transmittance of X-rays passing through $300\mu\text{m}$ beryllium, diamond and aluminum. From this point of view, beryllium, diamond and aluminum may be suitable windows depending on the desired X-ray energy. In our simulation, a diamond substrate is used in view of the fact that the diamond has the best thermal conductivity and mechanical properties.

In order to evaluate the influence of substrate thickness on the X-ray intensity, several different diamond substrate thicknesses ($200\mu\text{m}$ to $1000\mu\text{m}$) were simulated with the X-ray energy threshold of 4 keV and 10 keV. An optimized W-MMI ($2.0\mu\text{m}$ thickness) was used for these calculations with an electron beam energy of 30 keV. As illustrated in figure 5(b), compared to the $200\mu\text{m}$ case, the X-ray intensity of $1000\mu\text{m}$ case decreased by 48.6% and 22.3% with the X-ray energy threshold of 4 keV and 10 keV. Figure 5(b) also shows that the X-ray intensity with X-ray energy threshold of 10keV decreases slower than that of 4keV because the main absorption lies in the energy range 0–10 keV as shown in figure 5(a). However, $300\mu\text{m}$ diamond just attenuate about 3.8% of X-ray intensity with the X-ray energy threshold of 10 keV. The simulation results therefore indicate that optimizing the thickness of the diamond substrate can dramatically improve the X-ray intensity. It is worth noting that this is for low energy situations (30 keV). The attenuation of high energy X-ray will be reduced because the X-ray attenuation length is approximately proportional to the third power of X-ray energy. The thickness of the diamond substrate was chosen to be $300\mu\text{m}$ to balance competing requirements between mechanical strength to act as a vacuum window for a transmission X-ray source, thermal dissipation, and X-ray transmission.

For TLGI interferometer, the spectrum of the X-ray source is also important (Thüring and Stampanoni 2014). So the spectrum of X-rays at the exit surface of the substrate as a function of MMI thickness was also simulated. Here the results for three MMI materials at 90 keV incident electron beam energy are presented in figure 6–figure 8. The substrate is set to be $300\mu\text{m}$ thick diamond. Note that the previously calculated optimal thickness of the MMIs maximized the total X-ray production per incident electron with a low X-ray energy threshold. If instead the optimal X-ray flux is desired for a selected narrow energy bands, the optimal thickness may be different in principle. However, the difference is typically small for most practical applications.

Next the angular distribution of X-ray intensity of the transmission MAAT source is studied to understand how it may impact the FOV of a TLGI interferometer. For this calculation, the X-ray intensity of the MAAT source are recorded by a series of detectors placed every 5 degrees on the perimeter of a circle centered on the MAAT-electron beam interaction point. An X-ray energy threshold of one third of the incident electron energy was implemented to remove the effects of beam hardening. Figure 9 shows the angular distribution of X-ray intensity of tungsten microstructured array anode target (W-MAAT) with optimal thickness for 60 keV, 90 keV and 120 keV electron beam energy. The X-ray intensities was rescaled with respect to the maximum value instead of the absolute X-ray intensities. Since the bremsstrahlung double differential cross-section is a function of angle, the angular distribution of the generated X-rays is anisotropic and depends on the electron energy (Koch and Motz 1959, Tseng *et al* 1979). For 90 keV electron energy, the X-ray intensity at 20-degree is 5% less than 0-degree. Figure 9 shows that for most imaging applications of transmission MAAT source with the MMI thickness equal to the optimal thickness, the angular distribution of X-ray intensity of the transmission MAAT source is reasonably uniform within an angular range of $\pm 20^\circ$.

4. Thermal analysis

When an electron beam interacts with the MAAT a majority of the electron power is converted into heat. For a stable operation, the maximum temperature of the MAAT should be kept much lower than the melting point of materials of both MMI and diamond substrate.

It is important to note the difference between the total incident electron beam power and the electron power absorbed by the anode. The standard method of specifying the power of an X-ray source is through the total incident power which includes the power that is carried away by backscattered electrons and secondary particles and is therefore not absorbed by the MAAT. According to the simulation the ratio of power absorbed in the MAAT to the total incident electron beam power is 85.0% and as little as about 1.0% of total incident electron beam power is converted to X-rays. For example, an electron beam incident with 400 W total power only deposits 340 W in the MAAT.

To understand the maximum power load that can be applied to the MAAT without melting the MMI structures a finite element model of the W-MAAT was created and the thermal transport simulated. The incident electron beam footprint on the MAAT was modeled to be $100.0\mu\text{m}$ diameter circle and assumed to be uniformly distributed. The MMI region was a

$120.0\mu\text{m} \times 120.0\mu\text{m}$ square area comprised of $3.0\mu\text{m} (p) \times 120.0\mu\text{m} (w) \times 8.4\mu\text{m} (h)$ microstructured emitter, as shown in figure 1(a). The anode diamond substrate was set to 10 mm round diameter and 0.3 mm thick. The temperature along the edges of the substrate was assumed to be 21.0°C as the boundary condition for thermal modeling. The substrates top and bottom surface were set with vacuum convection coefficient of $25.0 \text{ W/m}^2\text{K}$. Figure 10 shows the temperature distribution of W-MAAT with incident electron power 400.0 W. Figure 10(a) is the temperature distribution of whole MAAT, figure 10(b) is the temperature distribution of the zoom-in MMI, the maximum temperature is 1375.0°C . Table 1 listed the thermal modeling results of W-MAAT for different given electron power.

Our simulation considers the case in which the electron beam power is distributed uniformly across a circle within the microstructured area. This approach was adopted in part due to modeling efficiency and due to preference to be conservative in our estimates, so that we can understand the performance under more demanding conditions. However, in reality, the electron beam distribution is not uniform but instead has a Gaussian shape with full-width half max (FWHM) matching the size of the microstructured area. Because the uniform distribution used in the model has 7% higher maximum power density and it loads 23.9% more power on the microstructured region than in reality, we estimate that the maximum temperature obtained in our thermal model would overestimate by at least 10%. Based on the thermal analysis the gaps have a negligible effect on the thermal dissipation. Due to the $200.0\mu\text{m}$ -thickness diamond substrate will dominate the thermal conductivity the thickness of the diamond substrate was chosen to be $300.0\mu\text{m}$ in practice. For long time operation, the total incident electron power of 400.0W (340.0W absorbed power) on the $100.0\mu\text{m}$ diameter anode, the operating temperatures are 1375°C for W-MAAT, which is close to the recrystallization temperature (1400°C). Moreover, Tungsten carbide is easily formed by reaction of tungsten metal and carbon at $1400 \sim 2000^\circ\text{C}$, which will decrease the ability of heat dissipation.

The diamond substrate is typically actively cooled with a powerful liquid chiller that typically makes the effects of room temperature irrelevant. Likewise, the power supply high voltage and current are stable to within 1% and will not drive the system into instability. In principle there is a limit where the boundary conditions could cause instability in the system but with thoughtful design of the cooling and power supply these limits are easily avoided.

5. Advantages

As mentioned previously, the use of an absorption grating to mask the extended source is inefficient but works adequately for X-ray energies below 20 keV, however the performance degrades rapidly above 20 keV. Unlike the absorption grating, the transmission MAAT source works for X-ray energies up to 80 keV X-rays used in diagnostic X-ray imaging equipment. Due to the substantially lower electron penetration power than X-rays, the fabrication of the MAAT source should be much simpler than that of the absorption grating, especially for high energy X-rays. The thickness and AR of a gold absorption grating with 90% contrast and the optimal thickness of MAAT are summarized in table 2. For the transmission MAAT, the AR required for 80 keV is just 12.8 : 1, which is far less than the AR required for G0 with 90% absorption with $1\mu\text{m}$ opening width. Note that higher X-ray

energies require very thick gratings because absorptivity decreases with the third power of the energy (Thüring *et al* 2014). At the same time the field of view also shrinks rapidly with increasing X-ray energy due to collimation by the high aspect ratio absorption grating (e.g. only approximately 1.9mm at 60 keV). This partly explains why high visibility TLGI interferometers have been realized with 20 keV X-rays, but higher energy X-ray imaging remains a challenge. In contrast, the field of view of a transmission MAAT source is big enough for imaging large samples.

The MAAT source provides the function of the G0 absorption grating without the compromise of losing half the flux. The G0 absorption grating is necessary for generating the required partially coherent illumination, but it also absorbs half the flux and reduces the source brilliance. Table 3 presents a comparison of the flux provided by two the two illumination schemes for Talbot microscopy. The percentage of incident electron power deposited in bulk W target is 62.0% for the normal incidence angle at the electron energy of 90keV, the remainder is backscattered. A G0 absorption grating with 33.3% duty cycle transmits one-third the incident flux. The percentage of power available for experiment in the combination of an extended X-ray source paired with an absorption grating is 20.6%, as shown in table 3. A MAAT source on the other hand preferentially deposits energy in the metal structures due to the difference in average path length of electrons and mass density between the MMI and substrate. For a W-MAAT source with period of 3.0 μ m and duty cycle of 33.3% giving 1.0 micron MMI separated by 2.0 microns of diamond, the percentage of incident electron power deposited in the W-MAAT is 85.0% and 47.5% of them deposited in the W-MMI. And thus the percentage of power available in the W-MAAT source is 40.4%. Compared to the combination of an extended X-ray source paired with an absorption grating, the brilliance per Watt of incident electron energy can be increased by 1.96X using a MAAT source. The MAAT source provides the required degree of coherence which does not come at the cost of loss of flux.

The elimination of the G0 has many advantages, on the one hand, it relieves the absorption grating fabrication difficulties. On the other hand, it means one less grating and the related inefficacy, electro-mechanical components, alignment and stability issues. Furthermore, Inverse Talbot-Lau geometry (Donath *et al* 2009) or Lau effect geometry (Momose *et al* 2011) which requires small period G0 absorption grating (or MAAT) can be achieved (Morimoto *et al* 2014, Morimoto *et al* 2015a, Morimoto *et al* 2015b). Using this geometry removes the requirement for a G2 absorption grating which may be removed entirely, further simplifying the interferometer by reducing the optical components required to a single phase grating.

6. Conclusion

The Monte Carlo simulation was used to optimize a novel transmission MAAT source which is the key component to translate high energy TLGI into practical applications. X-ray generation efficiency per incident X-ray electron, relative fraction of X-rays generated by the MMI and substrate, X-ray spectrum, and angular distribution as a function of incident electron energy and parameters of MAAT were calculated. Based on the simulation, we obtained optimal parameters of MAAT for 30 keV to 120 keV incident electron energies. We

also simulated the temperature distribution within the MAAT with electron for power loading on a MAAT using finite element analysis, so that the maximum allowable beam power loading for the stable operation of a transmission MAAT was derived. We believe that the calculation methodology and the MC simulation results presented in this paper can be generally applied for designing and fabricating a high brightness MAAT source which enable TLGI work at the higher energies.

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Figure 1.

A schematic of a transmission MAAT and simulation model, microstructure emitters in substrate (not in scale): (a) side view (b) top view. The gaps, or bridges, in the MMIs are included for increased mechanical stiffness and to reduce thermal stress.

Figure 2.

X-ray production efficiency per incident electron as a function of thickness for W-MMI, Mo-MMI and Cu-MMI at electron beam energy: (a)30keV; (b)60keV; (c)90keV; (d)120keV.

Figure 3.

(a-c) Calculated optimal thickness of MMI (black line) and average path length of electrons of W, Mo, Cu (blue line): (a) W-MMI, (b) Mo-MMI, and (c) Cu-MMI; and (d) Optimal X-ray production efficiency with optimal thickness of the three MMI materials as a function of electron beam energy.

Figure 4.

Calculated X-ray production profile of optimal thickness of W-MMI(a), Mo-MMI(b) and Cu-MMI(c) at 90 keV incident electron energy.

Figure 5.

(a) Transmittance of 0–120 keV X-ray through 300 μm thick diamond, beryllium, and aluminum; (b) Influence of the diamond substrate thickness on X-ray intensity.

Figure 6.
Calculated X-ray spectrum of W-MMI of different thickness at 90 keV incident electron energy.

Figure 7.
Calculated X-ray spectrum of Mo-MMI of different thickness at 90 keV incident electron energy.

Figure 8.
Calculated X-ray spectrum of Cu-MMI of different thickness at 90 keV incident electron energy.

Figure 9.
The angular distribution of X-ray intensity behind a transmission W-MAAT for different electron beam energy: (a) Z-X-plane direction; (b) X-Y-plane direction.

Figure 10.
Temperature distribution of Finite element analysis result of W-MAAT with electron power 400.0 W: (a) whole W-MAAT; (b) zoom-in MMI.

Table 1.

Finite element analysis result of W-MAAT at given powers.

Total Incident Electron Power (W)	Electron Power Absorbed by W-MAAT (W)	W-MAAT Max Temp (°C)
100.0	85.0	359.6
200.0	170.0	698.2
300.0	255.0	1033.9
400.0	340.0	1375.0

Table 2.

Limitations imposed by G0 and optimal thickness of W-MAAT.

Energy	20 keV	30 keV	60 keV	80 keV
G0 Thickness (assuming Au grating material and 90% absorption)	$15\mu m$	$44\mu m$	$269\mu m$	$563\mu m$
AR required for G0 with 90% absorption with $1\mu m$ opening width	15 : 1	44 : 1	269 : 1	563 : 1
Field of View ($L_s = 250mm$)	$33.3mm$	$11.4mm$	$1.9mm$	$0.9mm$
Optimal thickness of W-MAAT	$0.9\mu m$	$2.0\mu m$	$8.4\mu m$	$12.8\mu m$

Table 3.

A comparison of the flux provided by two illumination systems for Talbot microscopy: (i) an extended bulk tungsten source and G0 grating, (ii) a MAAT source.

	% incident power deposited in target (backscattered)	% absorption power deposited in W	% absorption power deposited in diamond	% power transmitted by G0	% power available
Extend source + G0	62.0%(38.0%)	62.0%	NA	33.3%	20.6%
MAAT	85.0%(15.0%)	47.5%	52.5%	NA	40.4%