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Hrdý J
Institute of Physics AVČR, Na Slovance 1999/2, Praha 8, 182 00, Czech Republic

Oberta P
Rigaku Innovative Technologies Europe S.R.O., Novodvorská 994, 142 21, Praha 4, Czech Republic

Corresponding Author:
Hrdý J
Institute of Physics AVČR, Na Slovance 1999/2, Praha 8, 182 00, Czech Republic

Diffractive-refractive optics-possibility of long distance communication by X-rays

Hrdý J and Oberta P

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Abstract
A novel concept is introduced to overcome the communication blackout of returning space carriers to earth from space. The concept is based on crystal optics working is a special refractive – diffractive régime. The crystal arrangement offer several advantages compared to previously introduced concepts, like light weight, stiffness and easy to align design. All these properties are very important when it comes to space born optics. Several possibilities are introduced and elaborated showing various performances of such a unique X-ray space collimator.

Keywords: Communication blackout, X-ray collimator, refractive – diffractive optics

Introduction
Recently, many papers were published on a topic called communication blackout [1, 2, 3, 4]. This communication blackout is connected with returning space carriers from space through the earth atmosphere. Due to the entering speed, the heat created by air through friction on the carrier body creates plasma which acts disruptively for any earth to space craft communication based on radio waves. A solution may be to use X-rays of the energy around 10keV instead of radio waves for the communication during this entering period. We can look at this problem from several aspects. The most critical is the X-ray photon transport over a large distance from the space craft to ground control. The reason is the loss of intensity due to two main reasons. First because of absorption of X-rays in air and secondly due to the divergence of the X-ray beam. The absorption problem can be solved with a proper energy range. The divergence problem can be solved by collimating the radiation.
The focus of this paper is on the design of such a crystal collimator for X-ray space communication. In recent papers several optical communication systems were proposed based on total reflection optics or multilayer coated optics. Systems based on these principles are complicated to manufacture, large and bulky. In this article we will discuss the possibility to use an X-ray collimator based on diffractive-refractive crystal optics (DR optics) [5, 6, 7].
X-ray DR optics is based on the diffraction from perfect crystal whose diffracting surface is properly profiled (Not bent). Due to the combination of diffraction and refraction effects the diffracted radiation may be modified, e.g. focused or collimated. In the past, we have used the diffraction on longitudinal parabolic groove produced to symmetrically or asymmetrically cut perfect crystals to sagittal focus synchrotron radiation. Here the crucial role is played by inclined diffraction.
The interest in inclined diffraction optics increased, after it was applied at synchrotron sources with high heat load [8, 9].
For our X-ray communicator design, we propose four parabolic grooves manufactured into two channel-cut single crystals. These crystals will be arranged in a dispersive (+, +) geometry. Originally this design was proposed for focusing X-ray synchrotron optics. In order that the outcoming beam should have the same direction as the incoming beam a Bartel geometry is proposed [10, 11, 12]. In [13] we demonstrated the focusing in laboratory conditions. However, the application of such DR optics as the collimator for long distance space communication requires a much more complex analyses of the beam intensity loss. Finally, in [14] and [15] it was shown that also a transversal groove can create a focusing effect in meridional direction. Balyan [16] showed that a parabolic depression may be used to create a 2D focusing. Obviously, these methods may be also used for collimation.

1. Theory

Figure 1 shows a scheme of a sagittally focusing X-ray monochromator. It is composed of two channel-cut single crystals in a dispersive arrangement (-, +, +, -). Longitudinal parabolic grooves are manufactured into all four diffraction surfaces. Due to the inclined surface of the parabolic grooves and due to the refraction effect occurring during the inclined diffraction, the diffracted rays from the first channel–cut crystal become slightly sagittally divergent. This divergence is canceled by the second crystal in dispersive arrangement [17].

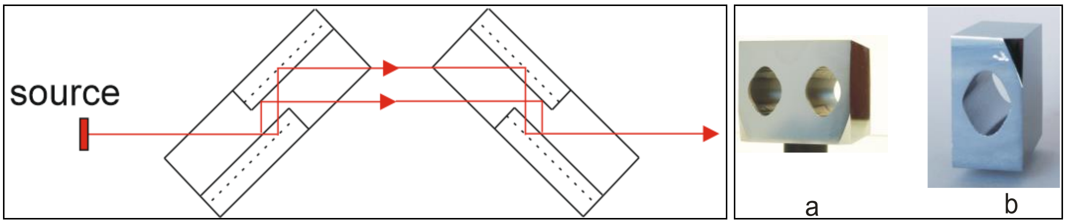

Fig 1: Double crystal set up of two collimating crystals

Figure 1 shows a vertical line source like from a commercial X-ray tube. Let us consider a system, where the focal spot is placed far from the source (i.e. collimator). From each point of the source, the diffracted beams propagate in the same direction. Theoretically, the image of the source corresponding to each point of the source should be a horizontal line whose length is the same as the width of the groove. All the beams are vertically adding up together and increase the final intensity. From the theory the sagittal deviation δ, after the inclined diffraction, is given by [6, 7]:

$$\delta = K\tan\beta \qquad (1)$$

Where β is the angle between the crystal surface and the crystallographic planes and K (see later) is $K = 4.8 \times 10^{-5}$. Differentiating formula (1) we get:

$$\frac{d\delta}{d\beta} = K(1 + \tan\beta^2)$$

For $\beta = 45°$ is $\frac{d}{d} = 10^{-4}$. This means that if we want to correct the angle deviation δ by one arc second (at β = 45°) we need to change β by 2.8°. Compared to a space communication system based on total reflection, this correction for a symmetric Bragg diffraction system is very easy to do. The basis for calculating the distance *f* between the collimator and the focal distance is:

$$f = \frac{S}{(2NKSa-1)} \qquad (2)$$

Where S is the distance between the X-ray source and the crystal collimator, N is the number of diffraction events (on fig. 1 N = 4) and "a", is the parabola parameter ($y = ax^2$), for a silicon crystal $K = 1.256 \times 10^{-3}$. d(h,k,l)[nm]. λ[nm]. If the denominator in equation (2) is zero, then the system is collimating. In that case,

$$a = \frac{1}{2NKS} \qquad (3)$$

The calculation for wavelength WLβ1 (λ = 0.122 nm), diffracting from Si planes (1,1,1) (d(111) = 0.313 nm) for S = 1000 mm and N = 4 we get the parabola parameter a = 2,595 mm^{-1}. The Bragg angle in this case is θ = 11.26°. The calculated parabola parameter seems to be quite large, and it makes the groove very narrow and deep. The broader the parabolic groove is, the higher is the amount of diffracted X-rays and the more intensity we get. A very deep groove also needs larger crystal. From this we can conclude that an ideal collimator should have rather a broad and shallow parabolic grooves, i.e. to have the parabola parameter a as small as possible. There are several possibilities how to achieve this.

1a)

One possibility to decrease **a**, is to increase the number N of diffracting events (see fig.2)

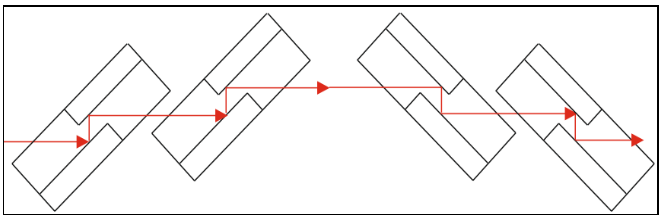

Fig 2: A set of four crystals in order to increase the number of diffracting events

It seems that the crystal arrangement has to be symmetrical in order that the small sagittal divergence of the beam caused by the left side of the collimator be fully compensated by the right side. However, as the sagittal divergence of the beam gradually decreases from the first crystal to the last one, the individual rays gradually income on slightly different place of the parabola when diffracted. To remove this problem, the parameter of the parabola a should be slightly corrected for every diffraction surface. So even if the system is symmetrical from the point of view of crystals, it is not fully symmetrical from the point of view of grooves. Another possibility seems to leave the grooves identical but to correct the distance between neighboring diffracted surfaces.

1b)

Another approach is through increasing the factor K. Beside a proper choice of diffracting planes (H, K, L), we can make such a groove into the crystal, whose surface forms with the diffracting planes a specific angle α. The diffracting planes has to be oriented in such a manner, that the diffraction (at the bottom of the groove) will be asymmetric. In that case, we need to multiply the factor K by [18]:

$$\frac{2 + \frac{\sin(\theta-\alpha)}{\sin(\theta+\alpha)} + \frac{\sin(\theta+\alpha)}{\sin(\theta-\alpha)}}{4\cos\alpha}$$

Then we obtain,

$$\delta(\alpha,\beta) = K\left[\frac{2+\frac{\sin(\Theta-\alpha)}{\sin(\Theta+\alpha)}+\frac{\sin(\Theta+\alpha)}{\sin(\Theta-\alpha)}}{4\cos\alpha}\right]\tan\beta \quad (4)$$

For example, for α = 8°, the term in square brackets is 2.01 and the angle between the impinging beam and the crystal surface is Θ - α= 3.26°. For this case, the parabola parameter is **a** = 2.59/2.01 = 1.29, which seems to be acceptable. The Darwin-Prince curve is for the impinging beam broader, what means a higher diffracting intensity. On the other hand, in order for the beam to reach the bottom of the groove, the groove has to be very shallow and/or the crystal should be very long.

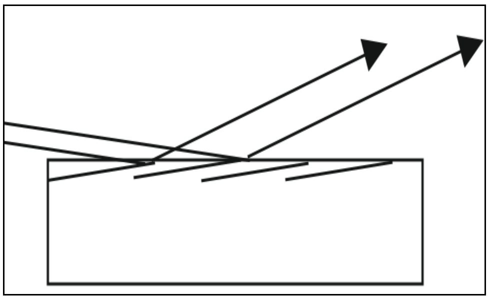

Fig 3: A long crystal with a shallow groove

A general and very complex formula for the asymmetric diffraction was calculated in [19, 20], which gives the value 1.72 in square brackets and thus slightly higher a. Similar problem was also solved in [21, 22]. Very important consequence of introducing asymmetry α is to increase δ. (We need to note that the increase of the parameter S, decreases the acceptance angle of the incoming radiation and thus also the diffracted intensity).

1c)
From our point of view, the most favorable solution would be to divide the parabola shape into segments. This way we create a diffraction surface which is similar to Fresnel zone plates. In this case we don´t have to think about the groove depth problem.

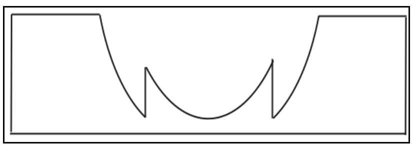

Fig 4: Fresnel zone plate like grooved surface

The above mentioned three approaches can be combined. For example, a collimator made of two channel cut crystals, with an asymmetry angle of α = 8° and a Fresnel like surface grooves could very well work for the energies mentioned in this paper. We still count with a source distance of S = 1000 mm. If we would like to move the focal point from infinity to a distance of 100 km, then we just need to increase S by 0.605 mm. From this, it is apparent that the fine tuning of the focal distance is very sensitive. It is necessary to say, that this model, even if it worked relatively well in our experiments, did not give ideal focus. A more detailed study [23] showed, that neither focusing nor collimating is ideal. The fact that the sagittal divergence created by the diffraction on the inclined surface on the first crystal is fully compensated by diffraction on the second crystal in dispersion position (as was mentioned in the previous paragraph) is not valid for all rays. This is discussed in more detail in [23] and is shown on the DeMond diagrams (fig.5).

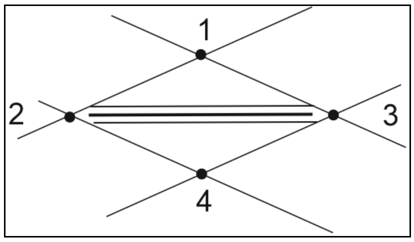

Fig 5: DuMond diagram for dispersion arrangement

A full compensation is realized only in the line between points 2 and 3. For the case of simplicity, let us imagine that the rays coming out of the collimator lay approximately in the horizontal plane. They have a small vertical spread given by the distance between points 2 and 3. Points 1 and 4 represent the maximum sagittal deviation. All rays impinging on the bottom of the groove are fully collimated. In these points the sagittal deviation is zero and the whole DuMond area is diffracting (area between points 1, 2, 3 and 4). This situation is shown in fig.6.

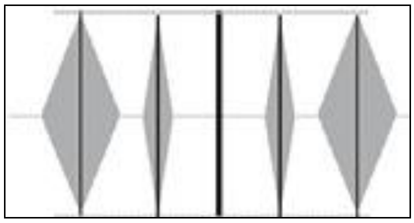

Fig 6: This figure schematically shows the diffraction from whole parabolic groove. The vertical lines represent the meridional direction of the crystal diffraction. The grey area represents the sagittally scattered beams.

From fig.6 we can see that the sagittal scattering increases with increasing distance from the middle of the groove. The upper and bottom part represents a perfect collimation. This corresponds to points 2 and 3 in the DuMond diagram. It is obvious that the largest contribution to the collimating effect is from the bottom of the groove and with growing distance from the bottom to the sides, the collimation gets weaker. This is in agreement with what was discussed above that an ideal groove should be broad and shallow. The formulas mentioned previously (1) and (4) were derived from a simplified model of dispersion spheres [24, 25] where the spheres were replaced by planes. From formula (1) it is obvious, that if β is close to 90°, then δ approaches infinity, which does not make sense. Similarly, from formula (4), δ approaches infinity, if α is close the θ angle. It is obvious that an ideal groove should not only be shallow but should also have rather small asymmetric angle α. To determine the limiting values of α and β when our formulae can be used would require a deeper theoretical investigation [19, 20] or to perform and experiment similar to [26] but for (+, +) dispersive arrangement. In [19] a more detailed calculation of relations between the inclination angle β, the asymmetry angle α and the sagittal deviation δ was performed. Our precise calculations indicate, that for a pure inclined geometry, the sagittal deviation δ is in agreement with formula (1) up to β = 80°. After this angle, δ starts to decrease in conflict with formula (1). For β approaching 90°, the sagittal deviation δ is close to 0.25°. It is obvious that for a parabolic groove formula (1) is a very good approximation. As was mentioned earlier, the formula (4), shows that by introducing an asymmetry angle α (for a given β), we can increase the sagittal deviation δ. Also, in this case a comparative calculation like in [19] is necessary in order to determine for which limiting angle α the approximation is still valid.

Until now we considered only the collimation in the sagittal direction. The crystal arrangement (+, +) limits the meridional divergence of the diffracted beam to very narrow angle, only several arc seconds. For a collimation to a focal spot which is 100 km away, the meridional size of the focus is about 500 mm.

2. X-ray source and other methods

One of the problems to solve in such an X-ray based communication system is the choice of energy and X-ray source. In our paper we choose the tungsten L-line, this choice is made upon the high energy and lower absorption in air. Obviously, the proper choice is higher energies. This creates certain boundaries in the choice of technology. Standard energies used in industry and academia are the K- and L-line of Cr (5.41 keV), Fe (6.40 keV), Cu (8.05 keV), Ga (9.25 keV), Mo (17.48 keV), Ag (22.16 keV), In (24, 21 keV) and the L-lines of W including it´s bremsstrahlung [27]. Most of these energies are provided by sealed tubes with power around 2 kW. This is a very weak tube for X-ray communication. Another possibility is a high-power transmission X-ray tube, which is very large and heavy. On the market we can also find high power micro focus X-ray tube with powers between 30W and 80W on a small 20 µm spot. Using a rotating anode X-ray source we can increase the load power from 1.2kW up to 8kW with a 70µm spot, but rotating anodes are very bulky. Last possibility are X-ray source with a liquid anode which currently reach very high power and relative high X-ray energies around the Ga line.

From the proposed possibilities the most suitable X-ray source from the point of view of size (including high voltage generator and possible cooling system) are micro-fucus high power X-ray tubes in a possible combination with focusing capillary or replicated optics.

There were previous attempts to use other type of optics for overcome the communication blackout. Most of them are based on total reflection from a pure substrate or a single metallic layer, grazing incident optics. The inspiration was taken from Wolter type astronomy optics used for collection of weak light on satellites. One of the latest examples is the European Athena project using a rotational symmetric silicon pore optics. Other example is the Czech nano cube satellites VZLU-1 having a Lobster Eye based multi foil optics on board. The drawback of all multifoil optics based on the Lobster Eye and Wolter type is, that it is large and heavy. Since it is made of several tens or hundreds of very thin glass or silicon foils it has to be very robust in order not to get misaligned during vibration created by start of space craft or even entering the atmosphere. An alternative for such optics can be a rotational symmetric replicated optics made of a rigid NiP body. One can even put several optics of different diameters together and nest them. Therefore, they are called nested optics and can be design for several wavelengths. Contrary the optics we propose, based on single crystal channel cut geometry is very light (only several tens of grams) and rigid. The two pair crystallographic planes are aligned and oriented by nature since we are using only one crystal. In the simplest design, using only two channel cut crystal we need to alight the two crystals toward each other.

Conclusion

The use of X-ray crystal collimator based on diffractive–refractive optics (DR optics) for long distance communication was discussed and proposed. It requires more intense X-ray source than the other system described in [28, 29] but such sources are today available. The main advantage of DR collimator is its simplicity, compactness and size.

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