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SYSTEM AND METHOD FOR HIGH ENERGY-RESOLUTION MEASUREMENTS OF X-RAY

TECHNOLOGICAL FIELD

The invention relates to X-ray spectroscopy and more specifically to X-ray spectroscopy of non-linear medium, such as crystals.

BACKGROUND

5 X-ray diffraction was discovered more than 100 years ago and has been used as a key tool in the studying of the structures of known crystals (and quasi-crystals). The information that can be obtained from X-ray diffraction is enormous and contains for example, the symmetry of materials, the locations of atoms within the unit cells, order or disorder of materials, variation of symmetry at phase transitions, chemical bond structures
10 and many more. It is therefore an important tool in many fields of research including physics, material science, chemistry, and biology. Indeed, X-ray diffraction systems are widely used in the academia and in many industries. Furthermore, the market and the number of companies developing X-ray diffraction systems are growing rapidly during the last decades.

15 X-ray diffraction examination utilizes the fact that crystals have periodic structures and therefore an electromagnetic radiation that is scattered from the crystals experiences destructive interference in most directions except from one direction in which the interference is constructive. The condition for a constructive interference is known as the Bragg's law: $2d \sin \theta = n\lambda$, where d is the spacing between the atomic planes, λ is
20 the wavelength of the x-ray radiation, θ is the incident angle with regard to the atomic planes, and n is any integer and represents the order of the diffraction.

While being successful, X-ray diffraction has several fundamental limitations. One of the major limitations is that the wavelength of the X-ray radiation has to be on the order of the distance between the atomic planes of the sample under investigation in order
25 to satisfy the Bragg's law. This limitation constrains the wavelength of the

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electromagnetic radiation to be on the order of 10^{-10} meters or less. Since the photon energies corresponding to this range of wavelengths are in the range of several kilo electron volts or more, which is on the same order as the binding energies of the core electrons, X-ray radiation interacts mainly with the core electrons in most materials.

5 Consequently, X-ray diffraction in most cases does not provide information on the valence electrons. Since valence electrons are the electrons that participate in the creations of molecules, a method that can be used to study their structure would provide evaluable insight into many electronic systems. In addition, in materials that contain heavy and light elements, X-ray diffraction will not be sensitive to the light elements since the number of

10 core electrons in heavy elements is much larger than the number of core electrons in light elements. Therefore, it would be desirable to develop a method that can provide an atomic selective diffraction so that information on each of the atom species in the sample can be accessible.

15 References considered as general background to the presently disclosed subject matter are listed below:

- B. Barbiellini, Y. Joly, and K. Tamasaku, Phys. Rev. B 92, 155119 (2015);
- K. Tamasaku and T. Ishikawa, Phys. Rev. Lett. 98, 244801 (2007);
- K. Tamasaku, K. Sawada, and T. Ishikawa, Phys. Rev. Lett. 103, 254801
- 20 (2009);
- K. Tamasaku, K. Sawada, E. Nishibori & T. Ishikawa, Nature Physics 7(9), 705-708 (2011).

Acknowledgement of the above references herein is not to be inferred as meaning that these are in any way relevant to the patentability of the presently disclosed subject

25 matter.

GENERAL DESCRIPTION

The present invention provides novel system and method for the study of electronic transitions in solids with atomic-scale resolution. The system of the invention is powerful and has a large signal-to-noise ratio, yet has a simple and cost-effective setup.

30 The invention can be applied as an effective tool in solid-state physics, material science, chemistry, and biology.

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Nonlinear interactions between X-rays and ultraviolet (UV) radiation have advanced the possibility that these types of interactions may be used to study the microscopic structures of chemical bonds and the density of valence electrons including the response to optical radiation with the atomic-scale resolution. These processes can be viewed as optically modulated X-ray diffraction, where the X-rays are scattered from optically induced charge oscillations. The UV radiation is associated with photon energies on the order of the valence electron binding energies (tens of electron volts). Experiments were conducted so far at large facilities such as X-ray Free-Electron Lasers or Synchrotron facilities. The access to these facilities is limited since there are only a few facilities in the world and their construction and running budget cost Billions of dollars.

The technique of the invention is based on the principles of X-ray spectroscopy of crystals utilizing parametric down conversion (PDC) occurring in crystals during X-ray pumping of a crystal, in order to evaluate the non-linear interaction between the X-ray and UV radiation in the sample, and thus determine various parameters of the sample. As appreciated, during the PDC process an incident x-ray photon generates an X-ray photon (of lower energy) and a UV photon which is absorbed by the irradiated material. The principles of the PDC, including energy and momentum conservations (phase-matching) between the three participating photons, enable obtaining the properties of the UV photon from the measurements of the incident (source) and generated (signal) X-ray photons. The measurements can be therefore done in air, and not in vacuum in contrast to other methods such as UV spectroscopy, angular resolved photo-electron spectroscopy, and soft x-ray inelastic scattering that can provide information on valence electrons, and the results represent the bulk properties and not just the properties of the material surfaces. Since UV energies are comparable to the energies of valence electrons, PDC into the UV regime provides information on the electronic structure of the valence electrons and on their interactions with external perturbations such as light, electric fields, magnetic fields, temperature, and pressure.

The X-ray spectroscopy system of the invention utilizes a simple, relatively cheap and commercially available X-ray tube sources, which are being daily used in laboratories, while performing high-resolution measurements of PDC from x-ray into UV. This is enabled, inter alia, by utilizing frequency selection by angular displacement of Bragg-based analyzer (separately from a detection plane), as well as momentum and/or

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phase-matching adjustment by angular displacement of either source channel or detection channel (or both channels).

Some of the challenges in observing parametric down conversion of X-rays into the UV are the low efficiency of the nonlinear process and the proximity of the phase-matching angle to the Bragg angle, which leads to background noise which is much stronger than the measured signal. According to the invention, these can be overcome by carefully designing the detection scheme. The system of the invention includes an X-ray detector which has a low dark count and thus has sufficiently high sensitivity enabling detection of weak signals, which enables to use a small, simple and cheap X-ray source that generates low-power photons, such as X-ray tube source. For example, the detector can be either a silicon drift detector, an avalanche photo-diode, or a camera with very low dark count.

Thus, according to a first broad aspect of the invention, there is provided a system for use in determining material properties of a sample of material, the system comprising:

an X-ray source configured and operable to generate a first X-ray radiation comprising source photons and direct them into an interaction region, such that when said sample is located in the interaction region said source photons affect parametric down conversion (PDC) effect of X-ray into ultraviolet (UV) in the sample; and a detector configured and operable to detect a second X-ray radiation comprising signal photons emerged from the sample in response to interaction between the source photons and the sample and generate data indicative thereof; wherein said source photons are of relatively low-power and said X-ray source and detector are positioned with respect to each other and with respect to the interaction region to meet a phase matching condition of the PDC effect, thereby enabling high energy-resolution measurements while operating with said relatively low-power source photons.

According to another broad aspect of the invention, there is provided a method for determining material properties of a sample of material, the method comprising:

irradiating the sample by a first X-ray radiation comprising low-power source photons propagating along a first optical path to thereby affect parametric down conversion (PDC) effect of X-ray into ultraviolet (UV) in the sample; and

detecting a second X-ray radiation comprising signal photons emerged from the sample and propagating along a second optical path, in response to interaction between the source photons and the sample, and generating data indicative thereof;

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wherein said first and second optical paths of said source and signal photons meet a phase matching condition of the PDC effect, thereby enabling high energy-resolution measurements.

In some embodiments, the X-ray source is an X-ray tube source, such as the
5 laboratory X-ray sources used in normal laboratory conditions.

In some embodiments, the source photons are of low-power not exceeding 10^9 photons per second.

In some embodiments, the first X-ray radiation is monochromatic.

In some embodiments, the detector has a low count rate detection resolution. In
10 one example, the low count rate is about one count per a few minutes.

In some embodiments, the detector is a silicon drift detector or an avalanche photo-diode detector or a low dark count rate camera.

In some embodiments, the system further comprises an analyzer located in optical path of the second X-ray radiation and being configured and operable to allow only signal
15 photons of a predefined energy matching the material UV properties to reach the detector.

In some embodiments, the material properties being determined comprise properties of valence electrons of the material.

In some embodiments, the material is a crystal.

In some embodiments, the energy-resolution measurements are in the range of a
20 few electron volts or a fraction thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by
25 way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic representation of the phase-matching condition of X-ray parametric down conversion into UV interaction;

Fig. 2 is a schematic diagram of one non-limiting example of a system configured
30 according to one embodiment of the present invention;

Fig. 3 is a block diagram illustrating a method for determining properties of a material according a non-limiting embodiment of the present invention;

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Figs. 4A-4C illustrate a graph showing experimental results of the dependency of the signal count rate as a function of the deviation of the pump angle from the phase-matching angle;

Figs. 5A-5B illustrate a graph showing experimental results of the analyzer scans
5 at different idler photon energies; and

Fig. 6 is a graph illustrating experimental results of the spectral dependence of the PDC in the LiF crystal, when the idler energy is chosen to be close to absorption edges of Li and F.

DETAILED DESCRIPTION OF EMBODIMENTS

10 Parametric down-conversion (PDC) of X-rays into ultraviolet (UV) radiation is a second order nonlinear process in which a pump photon interacts with the vacuum field to generate an X-ray photon and a UV photon. The X-ray photon is usually referred to as the “signal” photon and the UV photon is called the “idler” photon. Since the absorption length in the UV range is much shorter than the thickness of most samples, in a typical
15 experiment, only the signal photon is measured. Due to energy and momentum conservations, the photon energies and the angles of propagation of the generated photons are correlated. Moreover, since the signal and idler photons are generated simultaneously at the same position, the rate of the signal photons depends on both the X-ray and UV properties of the material. Hence, it is possible to retrieve the information on the UV
20 interactions from the measurements of the signal (X-ray) photons only. Since these interactions depend on the charge distribution and on the binding energies of the valence electrons, PDC of X-rays into UV can be used as a powerful tool for the studies of properties of the valence electrons in crystals.

The nonlinearity supporting X-ray PDC is originated from the Lorentz force and
25 spatial distribution of the electron density. This type on second order nonlinearity can be observed even in centrosymmetric crystals. It was shown that far from resonances the linear optical response and nonlinear second order optical response are related via the following expression:

$$\chi_G^{(2)}(\omega_s) = \frac{e}{2 \cdot \omega_s \cdot m \cdot c} \cdot \chi_G^{(1)}(\omega_i) \cdot \theta_{psi}, \quad (1)$$

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where $\chi_G^{(n)}(\omega_j)$ is n -th order of the G -th Fourier component of the optical susceptibility at the j -th frequency. The indices s and i represent signal and idler respectively, θ_{psi} is the polarization factor, e and m are the electron charge and mass respectively and c is the speed of light. Similarly to the optical regime, the generated
 5 photons satisfy energy and momentum conservation (phase matching).

Reference is made to **Fig. 1**, showing schematically the phase-matching condition of the X-Ray to UV PDC process. The energy conservation law can be written as $\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$ where the index p represents the pump beam (source photons). Since X-ray wavelengths are comparable to the interatomic distances, the momentum
 10 conservation is achieved by using the reciprocal lattice vector $\vec{G}$. In this case the phase-matching equation can be expressed as:

$$\vec{k}_p + \vec{G} = \vec{k}_s + \vec{k}_i, \quad (2)$$

where k_p , k_s , and k_i are the k -vectors of the pump, signal, and the idler beams respectively. θ_p , θ_s , and θ_i are the angles with respect to the atomic planes of the pump,
 15 signal, and idler respectively. k_B is the k -vector that satisfies the Bragg condition, and Δ is the angular offset of the pump from the Bragg angle.

Reference is made to **Fig. 2** showing a non-limiting example of a system for determining properties of a sample of material, in accordance with one embodiment of the invention. The system **100** includes an X-ray source **110**, which in this example is
 20 configured as a laboratory x-ray tube source, for generating the first X-ray radiation, an analyzer **120** for filtering the signal photons before hitting the detector, and a detector **130** for detecting the filtered signal photons. Also shown, a sample **140**, e.g. a non-linear crystal (the sample), located in the optical path from the source **110** to the analyzer **120**. The X-ray source **110** is configured to generate X-ray radiation including “source” low-
 25 power photons **Sc** and direct them along a first optical path OP1 into an interaction region **150** in which the sample **140** is located, to thereby cause for interaction between the source photons **Sc** and the sample **140** and affect PDC of X-ray into UV in the sample. The detector **130** detects “signal” photons **SI** emerging from the sample along a second

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optical path **OP2** in response to the PDC. Along the second optical path **OP2**, the analyzer **120** is positioned and angularly oriented with respect to the sample, and/or the signal photons emerging from the sample, in order to filter the signal photons by frequency and allow only the photons that are generated by the process of PDC and are correlated with the UV photons, which carry the information on the properties of the valence electrons of the sample material, to reach the detector. This increases the signal to noise ratio at the detector.

As a non-limiting example, the experimental system used by the inventors was as follows:

The X-ray tube is a Rigaku Smartlab 9kW X-ray diffractometer (XRD) with a rotating anode. The copper K α 1 beam is collimated and monochromatized by a parabolic multilayer mirror (**112** in Fig. 1) and a Ge(220) channel-cut monochromator (**114** in Fig. 1). The receiving optics include a Ge(220) 2-bounce channel-cut analyzer and a silicon drift detector. The analyzer **120** was calibrated in accord with copper K α 1 and K α 2 lines, and with bremsstrahlung radiation. A certain wavelength is selected by the input monochromator, the Bragg reflection is found from a reference Si (400) crystal and then the corresponding angle of the analyzer is found. The energy resolution of the analyzer **120** was estimated to be about 3 eV. The incident flux (the source photons) is of low power being about 4×10^8 photons/s. In general, the X-ray source can be configured to generate a low-power output of source photons as high as about 10^9 photons per second.

The expected signal is very weak, and the possible sources for noise are discussed below. The main source is the tail of the Bragg scattering. This is because the efficiency of the elastic scattering is about 8 orders of magnitude higher than the efficiency of PDC. Indeed, even after the analyzer crystal **120**, non-negligible photons from the Bragg tail are found. As the Bragg rocking curve is typically narrower than the PDC rocking curve, it is possible to distinguish between Bragg and PDC by scanning the angle of the source **Sc** relative to the Bragg angle. The next potential noise is Compton scattering. This noise depends weakly on angles than PDC so it is not expected to measure a rocking curve of Compton scattering. The Compton scattered photons are estimated to be with energy shift much larger than that of the signal photons (e.g., the Compton shift is about 95 eV and 150 eV for, respectively, the diamond and the Lithium Fluoride (LiF) experiments performed by the inventors as will be shown further below), thus the analyzer crystal **120**

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filters them out very efficiently. Another source for noise is X-ray Raman scattering, but this effect is very weak far from resonances.

Firstly, the Bragg reflection is found and the rocking curve is measured with the analyzer **120** tuned to the Co K α 1 line. Next, the source **110** and the detector **130** are moved to the PDC phase matching angles (corresponding to the first and second optical paths). The analyzer **120** is set to the photon energy of the signal photon. Slits **122** and **124** are used before and after the analyzer **120** to select a narrow angle range and to filter out residual elastic scattering. A scan is done firstly over the angle of the source photons **Sc** with respect to the crystal **140**. Then, the signal and signal to noise-ratio are optimized by scanning over the detector's **130** arm and the analyzer's **120** angle. The (220) reflection is used for the measurements in diamond and the (400) reflection is used for the measurements in the LiF.

Reference is made to **Fig. 3** illustrating a non-limiting example of a method, according to the present invention, for determining material properties. The method can advantageously be used for determining the material properties on an atomic scale while using X-ray radiation generated by a laboratory X-ray tube. The method enables energy-resolution measurements in the range of a fraction of an electron volt or up to a few electron volts. For example, properties of the valence shell of the material can be determined.. The method described herein below can be applied for example by using the system of Fig. 2. In step **310**, a sample of material is positioned on a platform and is irradiated by a first X-ray radiation that includes low-power source photons propagating along a first optical path such that the photons impinge upon the sample and interact with the material. The low-power source photons can be of a flow that do not exceed 10^9 photons per second. Accordingly, the source photons can be acquired from a simple X-ray tube. In optional step **320**, the first X-ray radiation can be filtered/adjusted to be monochromatic and by this increase the efficiency, though a non-monochromatic radiation can be used as well. In step **330**, the first X-ray radiation interacts with the material to thereby affect parametric down conversion (PDC) of X-ray into ultraviolet (UV) in the sample. After interacting with the material, the source photons of the first X-ray radiation generate UV photons that are mostly absorbed in the material and signal photons that are emitted from the material. In step **340**, the signal photons that emerge from the material while propagating along a second optical path, chosen to meet a phase-

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matching condition with the first optical path, can be filtered to include only signal photons with a predetermined frequency or energy matching the material's UV properties, i.e. by using the energy conservation law it is possible to learn about any of the following three by knowing about two of them: the source photons, the generated UV photons, and the signal photons. In step **350**, the filtered signal photons are detected. In step **360**, data indicative of the material properties can be generated based on the detected signal photons. For example, data about the valence shells of the material can be obtained. The detection of the low-power flow of the signal photons is done by utilizing a detector having a low count rate detection resolution, e.g. one count per a few minutes.

As mentioned, non-limiting examples and experiments demonstrating the use of X-ray tubes as a source for measurements of X-rays into UV PDC with energy resolution of a few eV are described below, which is comparable to the resolution achieved in synchrotron experiments. The effect is measured in diamond and Lithium Fluoride (LiF) crystals in the UV range of 30-65 eV (40-20 nm). In this regime, the effect is measured in LiF near the Fluorine LI edge at 45 eV and near the K edge of the Li at 55eV.

Reference is made to **Figs. 4A-4C** which show the dependency of the signal count rate as a function of the deviation of the pump angle from the phase matching angle, which is denoted θ_p . These measurements are done by scanning the angle of the source photons where all other angles are fixed. The solid lines are the theoretical calculations where the nonlinear susceptibility of Eq. 1 is used together with the coupled wave equations for the signal and idler operators in the slowly varying envelope approximation.

Fig. 4A depicts θ_p scans for the diamond crystal. The idler energy is 30 eV, and the phase matching angle is 2 mrad from the Bragg angle. It is clear that the PDC peak is shifted from the exact phase-matching angle. The same shift is shown in the theoretical calculations as well. In **Figs. 4B and 4C** the measurements for the LiF crystal with detector angles 0.3184 deg and -0.2185 deg in accord with Bragg angle condition are shown. These phase-matching angles are the two possible solutions of Eq. 2. The idler energy is 40 eV and the offset from the Bragg angle is 5 mrad. The calculated count rates are smaller by a factor of about 5 from the measured count rates and the measured rocking curves are broader than the theoretical prediction. The discrepancies in the widths can be explained by the mosaic spread of the LiF crystal. The zero on the abscissa corresponds

to the phase-matching condition. Dots with error bars are the experimental measurements; the solid lines are theoretical simulation. The PDC curves are the broad curves. The strong sharp peaks are due to the Bragg reflection. The theoretical calculations for LiF are multiplied by a factor of 5. The vertical error bars indicate counting statistics. To reconcile
 5 between the theoretical and measured efficiencies a quantum model, which considers local field correction for the nonlinearity, is most likely required. Both the theoretical calculations and the experimental measurements show the shift of the maximum PDC effect from the exact phase-matching angle. The shift depends on the phase-matching equation solution and the offset from Bragg condition. The measured efficiencies of the
 10 PDC for the two solutions of Eq. 2 (Fig. 4B and 4C) are not equal in agreement with the theoretical calculations.

To understand the shift in the curve with respect to the phase matching, it is noted that a large number of vacuum modes contribute to the PDC effect and there is a one to one correspondence between the photon energies and the angles. This relation is imposed
 15 by the phase matching condition. Since the detector has a finite aperture, modes at many photon energies and angles are collected. Moreover, modes with $\Delta k_z \neq 0$ also contribute to the count rate. The measured count rate is the sum of all the possible modes that are limited by the acceptance angle of the detector, by the bandwidth of the analyzer, and by the boundary conditions. In addition, since the nonlinearity increases as the idler photon
 20 energy decreases, the contributions of the lower photon energy modes are larger. This leads to the asymmetric line shape and to a shift in the rocking curve. The difference between the efficiencies at the different phase matching solutions can be caused by the fact that the angles of the idler photon with regard to the crystal surface are different for the two solutions.

Reference is made to **Figs. 5A-5B**. **Fig. 5A** shows the analyzer scans at idler photon energies of 30 eV (empty circles), 40 eV (full circles), and 50 eV (triangles). The size of the slit before the analyzer is 0.1 mm. Apart from the sharp and narrow elastic peak that corresponds to the residual elastic scattering, a broad peak is seen at each of the curves. The energy of this peak corresponds not to the selected idler photon energy but to the
 30 binding energy of 2p electrons in diamond at 11.3 eV. At this energy, the PDC effect is much stronger because of the resonant enhancement of the nonlinear susceptibility. The curves of the analyzer scans are broad because numerous vacuum fluctuation modes

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contribute to the count rate. The heights of curves decrease as the idler energies increase, as expected. The elastic peak is shifted from its position when the angles of the source and the detector satisfy the Bragg condition. This is because, unlike synchrotron experiments, the analyzer crystal and the sample have the same scattering planes.

5 Therefore, the angle of the photons emerging from the sample with respect to the atomic planes of the analyzer is shifted by rotation of the detector arm. **Fig. 5B** shows the analyzer scan for LiF crystal with idler photons at 40 eV. The main peak is around 5 eV and corresponds to the 2s electrons of Li atoms. The inset (ii) reveals a bump near 20 eV, which corresponds to the 2p electrons of the Fluorine atoms. Finally, inset (iii) shows a

10 bump that corresponds to the signal for the chosen idler energy at 40 eV.

Reference is made to **Fig. 6**, which describes the spectral dependence of the PDC effect in the LiF crystal, when the idler energy is chosen to be close to absorption edges. Each of the points in this figure represents the peak of the rocking curve at the idler energy of the horizontal axis. A strong peak near the L_I absorption edge of the Fluorine atoms is

15 seen. The peak is shifted from the tabulated value for neutral fluorine atom. However, the LiF crystal is ionic and thus the absorption edge is shifted to lower energies due to local field effects. The vertical solid lines represent the L edge of the neutral fluorine atom and the k edge of neutral lithium atom.

CLAIMS:

1. A system for use in determining material properties of a sample of material, the system comprising:
 - an X-ray source configured and operable to generate a first X-ray radiation
 - 5 comprising source photons and direct them into an interaction region, such that when said sample is located in the interaction region said source photons affect parametric down conversion (PDC) effect of X-ray into ultraviolet (UV) in the sample; and a detector configured and operable to detect a second X-ray radiation comprising signal photons emerged from the sample in response to interaction between the source photons and the
 - 10 sample and generate data indicative thereof; wherein said source photons are of relatively low-power and said X-ray source and detector are positioned with respect to each other and with respect to the interaction region to meet a phase matching condition of the PDC effect, thereby enabling high energy-resolution measurements while operating with said relatively low-power source photons.
- 15 2. The system according to claim 1, wherein said X-ray source is an X-ray tube source.
3. The system according to claim 1 or 2, wherein said source photons are of low-power not exceeding 10^9 photons per second.
4. The system according to any one of the preceding claims, wherein said first X-ray
- 20 radiation is monochromatic.
5. The system according to any one of the preceding claims, wherein said detector has a low count rate detection resolution.
6. The system according to claim 5, wherein said low count rate is about one count per a few minutes.
- 25 7. The system according to any one of the preceding claims, wherein said detector is a either a silicon drift detector or an avalanche photo-diode detector or a camera.
8. The system according to any one of the preceding claims, further comprising an analyzer located in optical path of the second X-ray radiation and being configured and operable to allow only signal photons of a predefined energy matching the material UV
- 30 properties to reach the detector.
9. The system according to any one of the preceding claims, wherein said material properties being determined comprise properties of valence electrons of the material.

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- 10.** The system according to any one of the preceding claims, wherein said material is a crystal.
- 11.** The system according to any one of the preceding claims, wherein said energy-resolution measurements are in the range down to a fraction of electron volt.
- 5 **12.** A method for determining material properties of a sample of material, the method comprising using the system of any of the claims 1 to 11.
- 13.** A method for determining material properties of a sample of material, the method comprising:
irradiating the sample by a first X-ray radiation comprising low-power source photons
10 propagating along a first optical path to thereby affect parametric down conversion (PDC) effect of X-ray into ultraviolet (UV) in the sample; and
detecting a second X-ray radiation comprising signal photons emerged from the sample and propagating along a second optical path, in response to interaction between the source photons and the sample, and generating data indicative thereof;
- 15 wherein said first and second optical paths of said source and signal photons meet a phase matching condition of the PDC effect, thereby enabling high energy-resolution measurements.
- 14.** The method according to claim 13, wherein flow of said low-power source photons do not exceed 10^9 photons per second.
- 20 **15.** The method according to claim 13 or 14, wherein said first X-ray radiation is monochromatic.
- 16.** The method according to any one of claims 13 to 15, wherein said detecting of the signal photons is characterized by a low count rate detection resolution.
- 17.** The method according to claim 16, wherein said low count rate is about one count
25 per a few minutes.
- 18.** The method according to any one of claims 13 to 17, further comprising filtering said signal photons to thereby allow only signal photons of a predefined energy matching the material's UV properties to be detected.
- 19.** The method according to any one of claims 13 to 18, wherein said material
30 properties comprise properties of valence electrons of the material.
- 20.** The method according to any one of claims 13 to 19, wherein said material is a crystal.

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21. The method according to any one of claims 13 to 20, wherein said energy-resolution measurements are in the range down to a fraction of electron volt.

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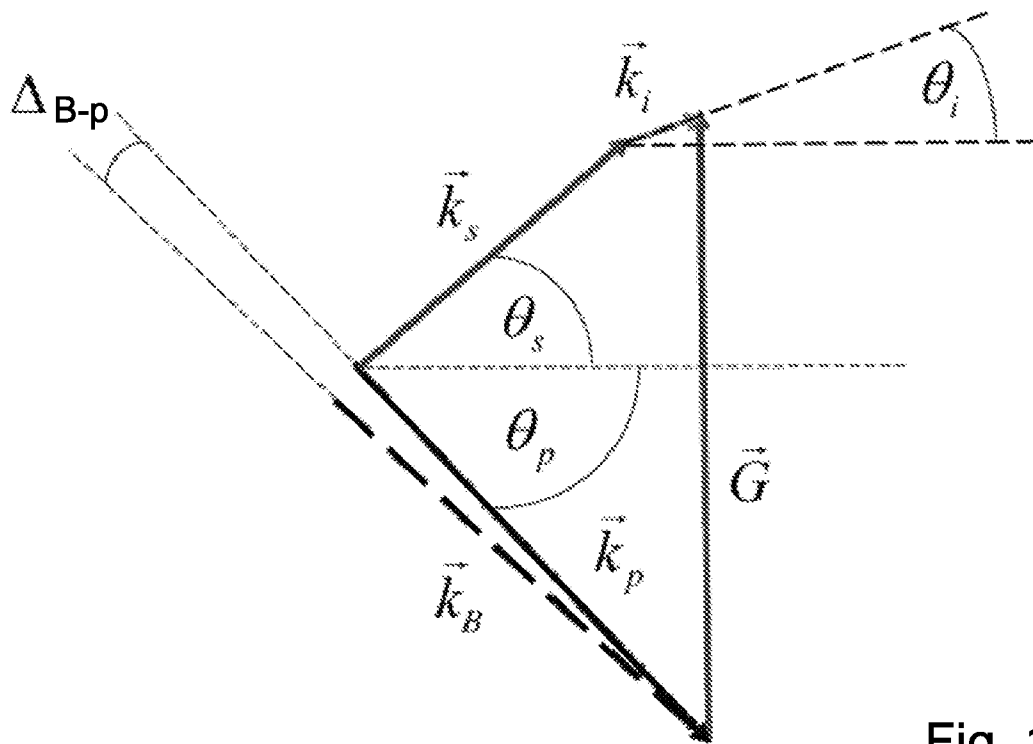


Fig. 1

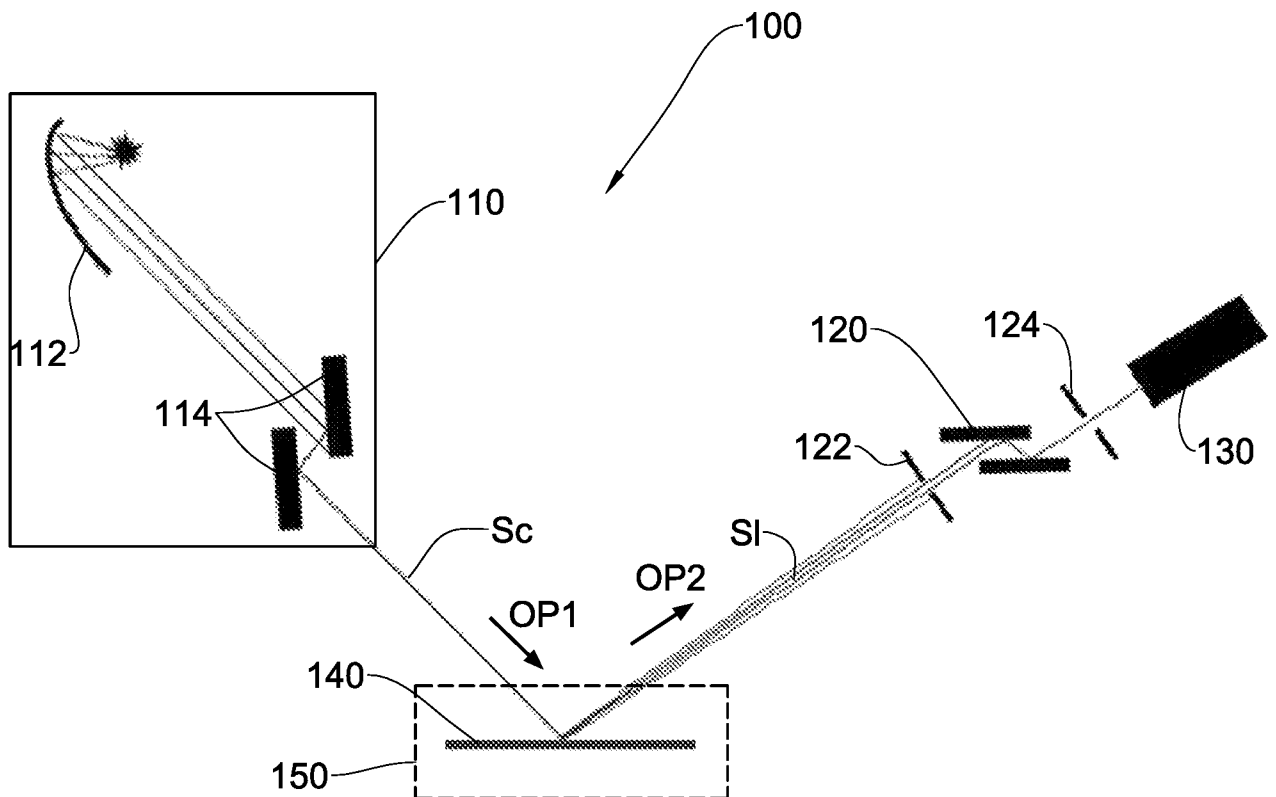


Fig. 2

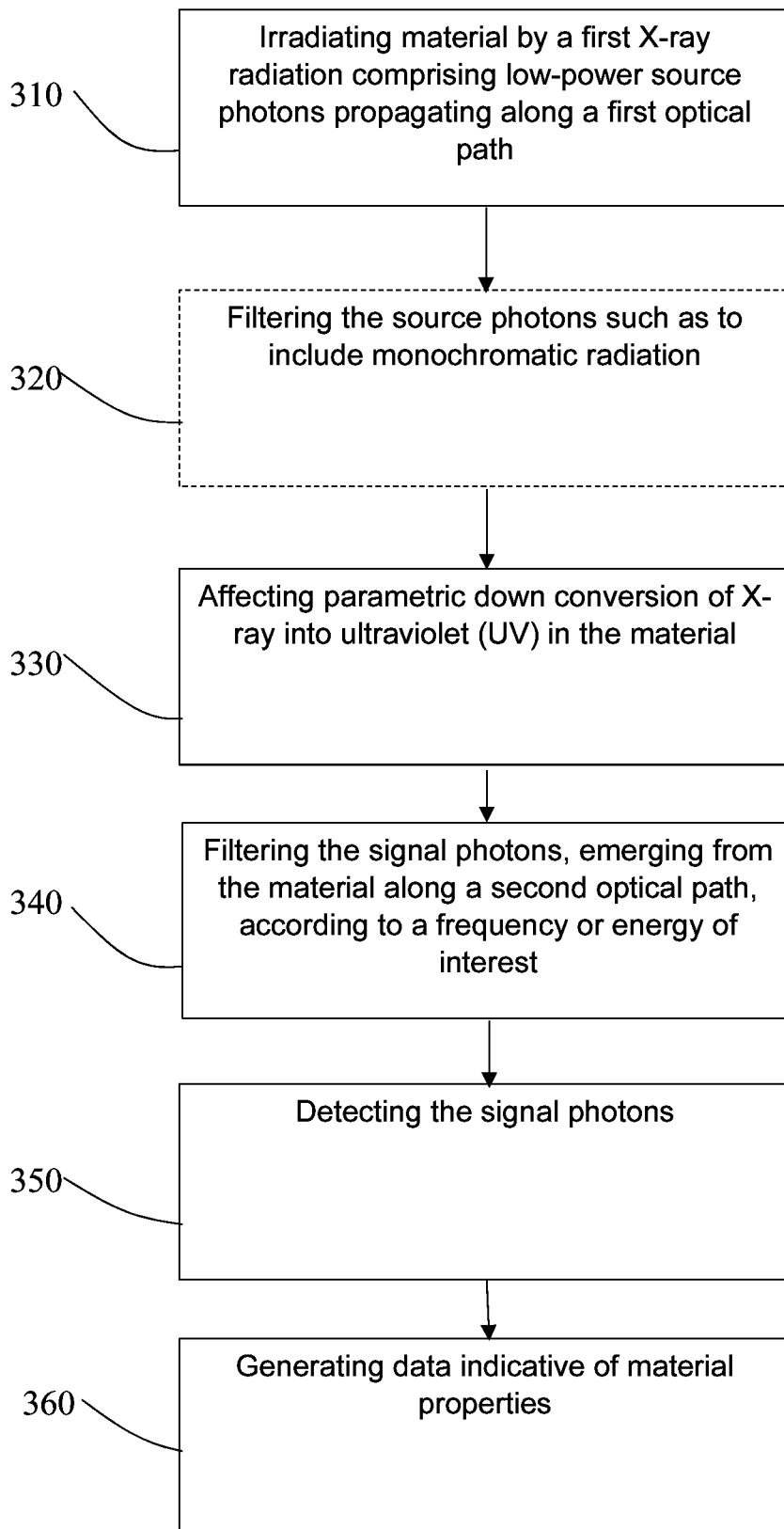


Fig. 3

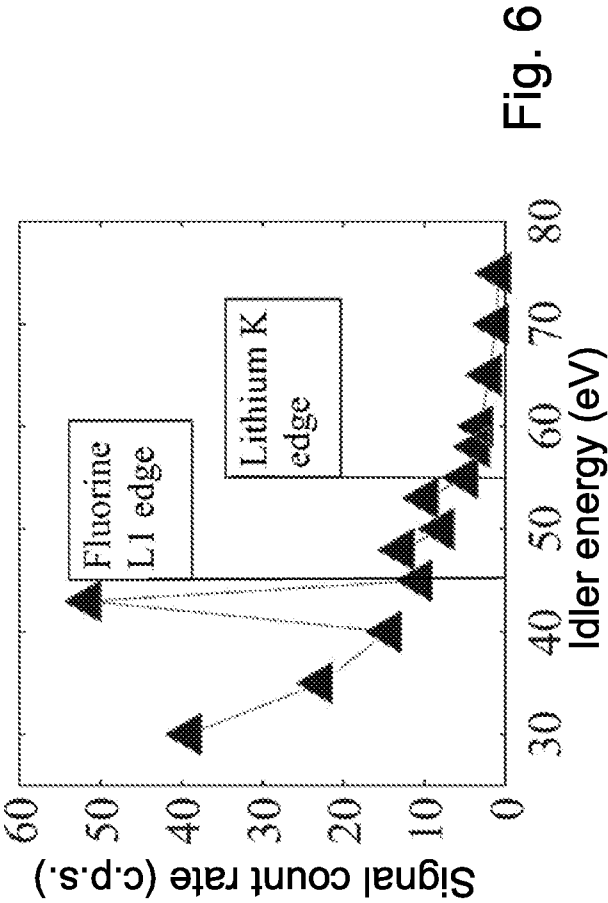
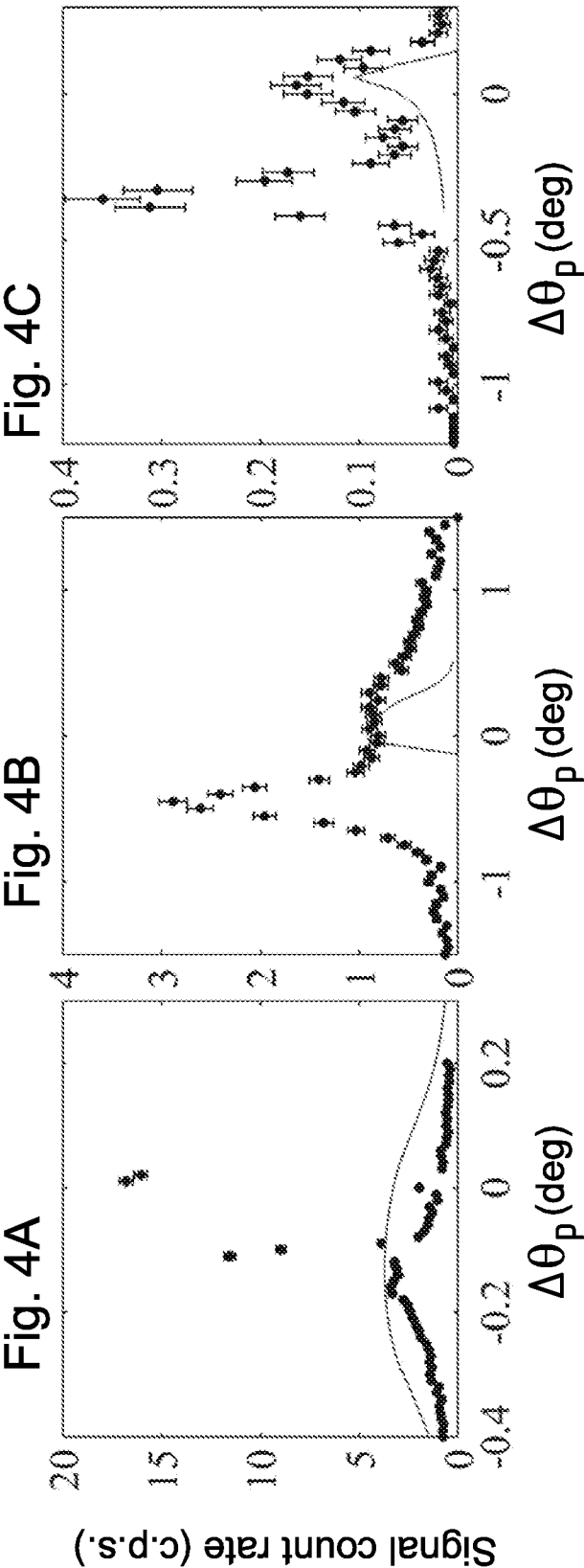


Fig. 5A

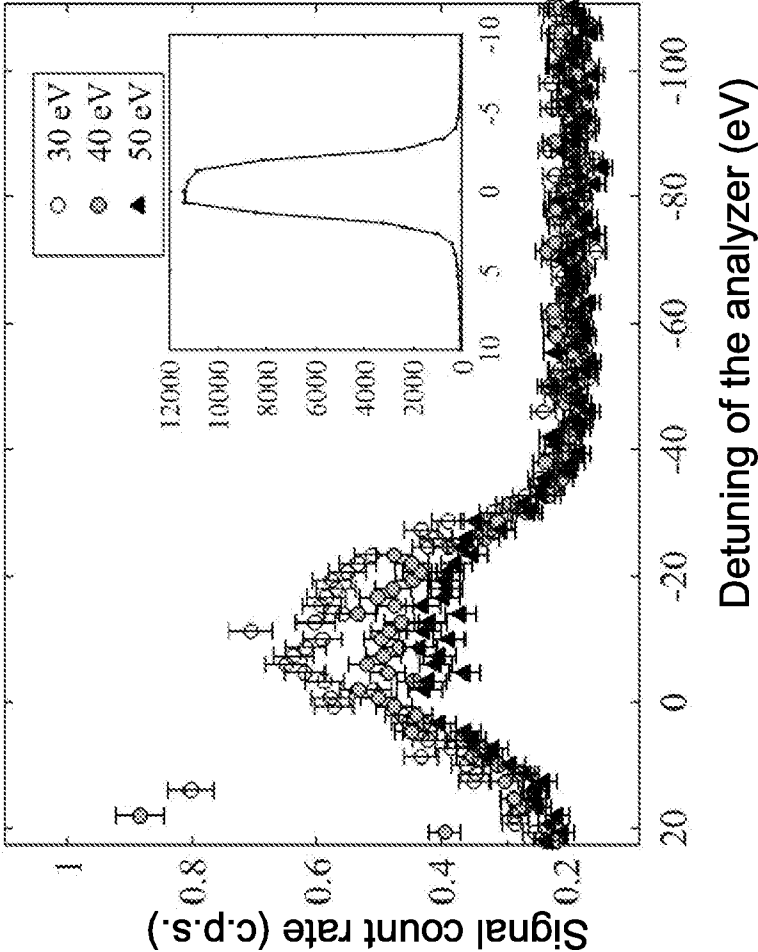
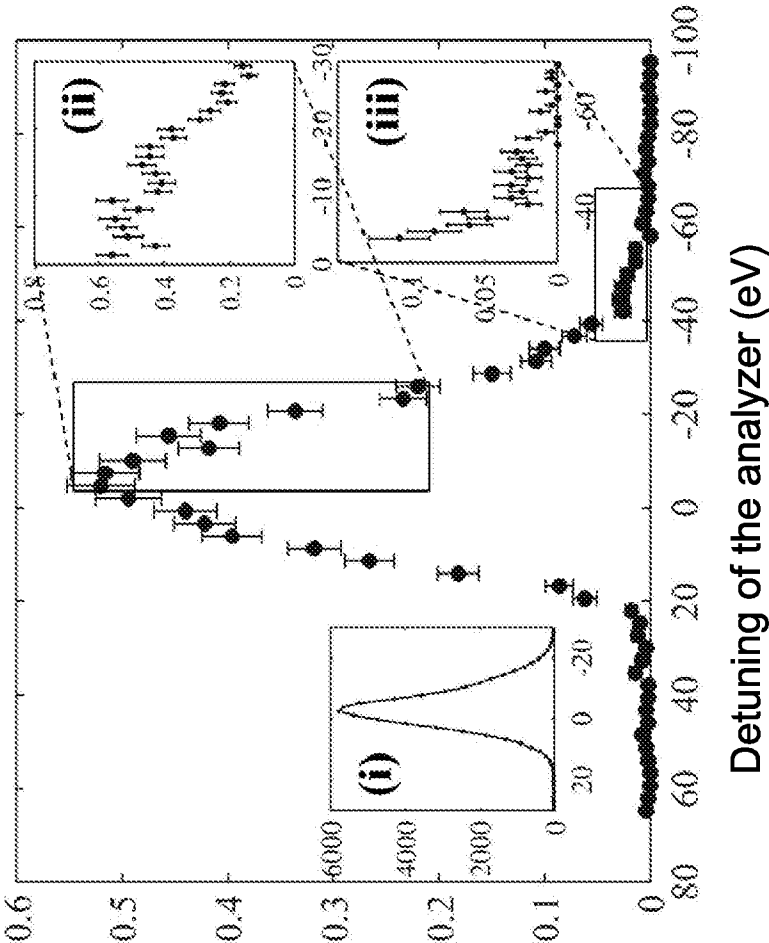


Fig. 5B



INTERNATIONAL SEARCH REPORT

International application No.

PCT/IL2018/050061

A. CLASSIFICATION OF SUBJECT MATTER

IPC (2018.01) G01N 23/22, G02F 1/37

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC (2018.01) G01N, G01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Databases consulted: Google Patents, Google Scholar, PatBase

Search terms used: X-ray, photon, parametric downconversion, idler, ultraviolet, phase match, non-linear, momentum conservation, valence, low-power, monochrom, filter.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Visualizing the local optical response to extremeultraviolet radiation with a resolution of $\lambda/380$, Nature Physics, vol. 7, issue 9, September 2011, pp. 705-708 Tamasaku et al. 30 Sep 2011 (2011/09/30) The entire document.	1-21
A	X-ray two-photon absorption competing against single and sequential multiphoton processes, Nature Photonics, vol. 8, April 2014, pp. 313-316 Tamasaku et al. 30 Apr 2014 (2014/04/30) The entire document.	1-21
A	Parametric down conversion of X-ray photons, Journal of Synchrotron Radiation, vol. 7, part 2, March 2000, pp. 81-88 Adams et al. 31 Mar 2000 (2000/03/31) The entire document.	1-21
A	US 3688124 A Freund et al. 29 Aug 1972 (1972/08/29) The entire document.	1-21

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search

18 Apr 2018

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/IL2018/050061

Patent document cited search report	Publication date	Patent family member(s)	Publication Date
US 3688124 A	29 Aug 1972	US 3688124 A	29 Aug 1972