Geometrical optical diode for natural (ambient) light

Gabriel Moagă-Poladian, Cătălin Tibeică and Dănuţ-Vasile Ursu

1 National Institute for Research and Development in Microtechnology – IMT Bucharest, Bucharest-Voluntari, Romania
2 S.C. ROVSOL S.R.L., Str. Gheorghe Petraşcu 67 E, Sector 3, Bucharest, Romania
E-mail: gabriel.moagar@imt.ro

Keywords: optical diode, natural light, asymmetric scattering, asymmetric absorption

Abstract
We present a device that acts as a diode for natural light. It has different transmission values when light travels in one direction and, respectively, in the opposite one. It relies on the geometric left-right asymmetry of scattering and absorption and uses diffuse light of whichever polarization and with a large spectral range.

1. Introduction

There are applications such as optical insulation, ring lasers, ultra-high power lasers, unilateral optical communications that require the passage of light from one direction to another while blocking (or at least reducing) propagation when light travels in the opposite direction. Several examples of such systems have been presented in the literature, see for example [1–12]. A more general theory is presented in [13] where the diode concept does not refer solely to optical beams. For such a device to be an optical diode, it must fulfil the non-reciprocity and/or nonlinearity condition, as described in [14]. Nonlinearity needs intense light beams in order to visibly manifest. Because of that, the nonlinear response to natural light is too small to be able to show a diode effect based on such a phenomenon. While most of the optical diodes presented in the literature are working best with collimated beams, there is no approach (at least to the best of our knowledge) of such devices that are able to work with natural, white light that is non-collimated, especially if we consider the spectral range from far infrared to ultraviolet. Since natural light will work only with linear devices because of its too low intensity to significantly excite nonlinear response, it is then obvious that such a diode-like behaviour can be obtained only with a linear system that gives rise to time reversal symmetry breaking. This time reversal symmetry breaking is one of the conditions to have a diode-like, asymmetric response.

It is the aim of this paper to present a solution to this problem. The device can work with broadband, diffuse and non-polarized light. It is a single passive device that uses geometric asymmetry of scattering for obtaining the diode-like, asymmetric response. The light must not be very intense since no nonlinear effect is used. Because of that, any input power gives rise to such a behaviour. Also important is the fact that the device is spectrally insensitive, preserving the same characteristics on a broad spectral range.

The paper is structured as follows. Section 2 describes the working principle; section 3 is devoted to the presentation of simulation results while section 4 is devoted to discussions. The paper ends with the Conclusions section.

2. Working principle

We start from the concept of geometric diode specific to graphene-based geometric diodes [15–20]. Such a graphene geometric diode works in its ballistic regime and makes use of the asymmetrical scattering of electron waves as they move through the device in one direction or in the opposite one. It is purely a geometric effect that ensures asymmetrical scattering and thus a difference in impedance seen by the currents passing in one way or in the opposite one. According to [14], the fact the graphene-based geometrical diode is not a non-reciprocal device gives rise to the fact that the rectification factor – defined as the ratio between the current in one direction and the...
current in the opposed direction – have a value close to 1, meaning a weak rectification effect. As opposed to graphene, in our case the reflective surfaces may have different types of behaviour. The most encountered ones are the specular, isotropic and Lambertian reflectivities, respectively. As will be seen later, this creates a difference as compared to graphene, giving rise to higher values of the rectification factor.

We make use of the asymmetric scattering that creates a difference in the transmission and absorption of light that is dependent on the propagation direction (left-to-right, respectively right-to-left). Starting from this idea, we devised an optical element that is strongly asymmetric. It is shaped as a cone with a planar base and having the top cut, see figure 1. Its internal surfaces (cone and base) are reflective and have reflectivity equal to $R$. At its base and at the top, the cone has two apertures of equal diameter centered around the symmetry axis of the cone.

A very small fraction of light passes directly, without any reflection, from the entrance aperture to the exit one. This happens since the structure is axisymmetric and the apertures are in line-of-sight of each other. The gross amount of light passes from one aperture to the other after suffering numerous reflections on the inner surfaces of the device. Part of light is transmitted, part of it is reflected. If $R < 1$, then part of light is also absorbed. Rigorously speaking [14], this device cannot be a true optical diode. For example, collimated beams as those emitted by lasers will have the same transmission whichever propagation direction is. However, for natural (diffuse) light things change significantly and the device becomes strongly asymmetric since it exhibits different absorption values when passing from left-to-right compared to the opposite propagation case, as is presented in section 3.

Figure 1(a) present the sketch of the device and its geometric parameters while figure 1(b) depicts the sectioned CAD model of the device.

3. Simulation results

The medium inside the diode is the same as that outside it and is totally non-absorbing (i.e. it has a zero absorption coefficient). We have considered three types of reflectivity: specular, isotropic and Lambertian, respectively. The specular one is the ‘mirror-like’ reflection when the incident beam is reflected to a single emerging beam that obeys the rule of reflection (equal incidence and reflection angles). The isotropic one scatters the incident beam in a $2\pi$ solid angle, the reflected intensity for each direction being the same whichever the angle of the incident beam. The Lambertian one scatters the light also in a $2\pi$ solid angle, but the intensity of the beam varies with the cosine of the angle between the incident beam and the normal to the surface.

It is important to underline the fact that we have considered the same inputs whichever the reflectivity type in order to be able to compare the results obtained for the three types of reflectivities considered.

The geometry used for simulations is presented in figure 1. The simulations were made in COMSOL, by considering more than 300,000 rays for each case. As mentioned, several types of inner surface reflectivity were considered: specular, isotropic and, respectively, Lambertian. In all cases, the surface reflectivity was taken equal to 0.99 while the length of the element is $L = 20$ mm.
We computed first the transmitted power for each of the two propagation directions (left-to-right, right-to-left) and then calculated the rectification factor by the formula:

\[ r = \frac{P_{LR}}{P_{RL}} = \frac{T_{LR}}{T_{RL}} \]  

(1)

where \( P_{LR} \) is the power transmitted from left-to-right while \( P_{RL} \) is the power transmitted from right-to-left, while \( T_{LR} \) and \( T_{RL} \) are the corresponding transmissivities of the device. If \( r = 1 \) it means that there is no rectification (zero rectification), the device behaving similarly whichever the propagation direction. Also, \( r > 1 \) means that the left-to-right direction is the preferred one (higher transmission), while \( r < 1 \) means that the opposite direction is favoured. Even if we call it ‘rectification factor’ it does not refer to optical rectification (which is a nonlinear phenomenon). It is solely used to describe the asymmetry in transmission.

We performed the simulations for cone angles up to 45° because, if the angle goes higher, the diode resembles more and more a cylindrical tube (is cylindrical, in fact an infinite radius cylinder, for an angle of 90°). Such a geometry, being symmetrical in the limit of 90° angle, presents no diode-like behaviour. Decreasing the angle to 0°, the device becomes again a simple, cylindrical tube (of finite radius this time) that again does not present diode-like behaviour. Because of that, we expect to have a certain angle value for which the rectification factor attains a maximum value.

| Reflectivity type | Angle of maximum \( r \) (°) | Max. value of rectification factor |
|-------------------|-----------------------------|----------------------------------|
| Specular          | 5                           | 1.55 →                           |
| Isotropic         | 30\(^\circ\)                | 2.80\(^\circ\)                   |
| Lambertian (diffuse) | 2\(^\circ\)    | 1.12\(^\circ\)                   |

\( ^* \) Better transmission direction opposite compared to that of specular reflection, as indicated by the arrows in the 3rd column (arrows are with respect to figure 1(a)).
Details regarding simulations are presented in the Annex to this article. The dependence of the rectification factor on the cone angle is presented in Table 1 for apertures diameter equal to 1 mm.

As is observed from Table 1, the rectification factor achieves a maximum value for certain, reflectivity-type dependent cone angle. The respective maximum values are mentioned in Table 2. It is thus observed that simulation results confirm our supposition that there is an angle for which \( \rho \) is maximum.

It is noticed from Table 1 that, for the case of specular reflection, the rectification factor decreases non-monotonically with the cone angle. More interesting, at an angle of 44\(^\circ\) reaches a value equal to 1 (meaning no rectification), after which it goes to values below 1, thus reverting the direction of preferred transmission. This means that the direction of higher transmission is changed as the angle is increased further from 44\(^\circ\). This effect is due to the way rays redistribute after the reflection for different cone angles. The isotropic case has a uniform increase with the angle up to an angle of 30\(^\circ\) after which it shows a very small decrease as the angle is increased further.

While the Lambertian reflection shows monotonically decrease of the rectification factor as the cone angle is increased, it reaches the no-rectification behaviour for the cone angle equal to 45\(^\circ\).

From Table 2 it is observed that the best values are obtained by the isotropic reflectivity case followed by the specular one.

For these angle values mentioned in Table 2, we have studied the dependence of rectification factor on aperture diameter. Details of simulation results are presented in annex.

Again, the preferred diode direction differs between the specular reflection case and the isotropic and, respectively, Lambertian ones.

Table 3 presents the graphs of the rectification factor versus aperture diameter.

It is seen from Table 3 that the specular surface has a non-monotonically variation with the aperture diameter. Two maxima are clearly visible. The isotropic surface has a monotonical variation with aperture diameter, variation that becomes slower at high apertures. The Lambertian surface has an almost monotonical variation of the rectification factor with respect to aperture diameter, with a small local maximum at a diameter

---

Table 3. The rectification factor as a function of aperture diameter (for the cone angle corresponding to the maximum \( \rho \) for each case). The preferred transmission directions are similar to those in Table 1.
of 2.2 mm. The increase of aperture at a given device length has as an effect the fact that more light that enters the device goes directly to the opposed aperture without experiencing any reflection/scattering. This means that a smaller fraction of the entry beam experiences asymmetrical scattering, leading to a decrease of the rectification factor. This is the reason for which, on average, the rectification factor decreases with the increase of aperture diameter whichever the reflectivity type is. It is interesting to note the fact that the monotonic behaviour shown by isotropic and Lambertian cases, respectively, suggests that decreasing aperture diameter below 1 mm would bring a higher value for the rectification factor. The same is not true for the specular reflection, where a further decrease of the aperture diameter does not seem to bring too much advantage as regards the magnitude of ‘r’. This difference in behaviour is due to the way in which scattering occurs when a ray bounces the reflective surface. A diffuse surface has a much higher scattering than the specular one. It is thus expected that decreasing the fraction of direct light (i.e. that fraction that goes directly to exit without any reflection) by decreasing the aperture diameter will favour the diode-like behaviour for the diffuse surfaces more than for the specular one.

Table 4 synthesizes the maximum value of rectification factor with respect to the corresponding angle and aperture diameter.

| Reflectivity type (angle) | Aperture of maximum (mm) | Maximum value of rectification factor |
|--------------------------|--------------------------|--------------------------------------|
| Specular (5°)            | 1.4                      | 1.64                                 |
| Isotropic (30°)          | 1.0                      | 3.60                                 |
| Lambertian (diffuse) (2°)| 1.0                      | 1.13                                 |

Table 5. Rectification factor for the serially connected diodes.

| Reflectivity type (angle, aperture diameter) | Number of serially connected diodes | Rectification factor | Preferred direction |
|---------------------------------------------|-------------------------------------|----------------------|--------------------|
| Specular (5°, 1.4 mm) | 2 | 1.769 | → (left-to-right) |
| Isotropic (30°, 1 mm)) | 2 | 8.294 | ← (right-to-left) |

Figure 2. The sketch of the geometry of the serially connected optical diodes considered in simulations.
It is seen from table 5 that the rectification factor for the isotropic case is high for the case of two serially connected diodes, being more than double as compared to similar single diode case. We may thus conclude that among the three types of reflection considered, the isotropic one gives the best results and shows a clear diode-like behaviour. One explanation for such a result is that the rays scattered at large angles with respect to normal to the reflection surface contribute most to the transmission asymmetry of the device.

It must be noted that while the rectification factor is enhanced in the case of the serially connected optical diode, its overall optical transmissivities (for the two propagation directions) are reduced as compared to the single optical diode.

It is seen from table 5 that the rectification factor \( r_{cd} \) of the serially connected optical diode is not simply the square of the rectification factor \( r_s \) of the single diode. By computing the square of \( r_s \) and dividing it by \( r_{cd} \), we obtain almost the same value of this ratio, with a difference of around 2.5 % between the two reflectivity cases considered in table 5. The results are shown in table 6. Thus, the approximate relation between \( r_{cd} \) and \( r_s \) is:

\[
\frac{r_s^2}{r_{cd}} = f \approx \text{const.}
\]  

The fact that \( r_{cd} \) is less than \( r_s^2 \) is because the input light distribution at the entrance of the second diode (and hence at the exit of the first one) differs from that of the first diode entrance aperture. In the latter case, the input intensity is uniformly diffuse (i.e. equally distributed as regards both intensity within aperture and its angular dependence) while at the second diode entrance things are changed (see tables A2 and A4 in the annex).

### 4. Discussions

The device can operate on a broad spectral range. This feature is given by the reflective nature of the device and by the spectral properties of the propagation medium existing inside the device. Thus, if the inside medium is air and taking into account the device size, then the optical diode may work from near UV to far IR. The limiting factor is determined by the metal layer deposited on the inner parts of the device. Reducing reflectivity degrades the diode-like behaviour of the device. For example, for Gold, this becomes highly reflective for wavelengths above 500 nm. Gold could represent a choice because the use of another metal, with better reflectivity in UV and visible such as Aluminum would bring the risk of formation of a thin oxide layer at the metal surface, changing reflectivity especially at large angles of incidence.

On the other part of the spectrum, at large wavelengths, the reflectivity decrease is given by the metal layer thickness. As is known, every conductor has a so-called skin depth that depends on material electrical conductivity and on the frequency of the incident radiation. For a given conductor, the skin depth increases as the radiation wavelength increases. For our device, we estimate that it can work up to around 20 microns. Thus, we may affirm that the device can work from visible to far IR, which is a very large spectral range. Going further to THz radiation would be problematic because of the skin depth. This problem may be solved by using thicker metal layers.

Another aspect that has to be considered when considering long wavelengths is diffraction. As wavelength increases so does the diffraction on the aperture. Our results are valid for the spectral range from UV to far IR, when diffraction aspects can be neglected. If the internal reflective surface has roughness, the diffraction occurs also on the surface elements that give rise to roughness. However, their simulation is extremely difficult because of several reasons:

(a) it is necessary to know the surface topography on a large area (several squared centimeters) with a resolution of better than 1 micron. This is very hard to determine experimentally, especially when the surfaces are curved and concave.

(b) Building the CAD model with such a spatial resolution would create a very big file that is difficult to manipulate.

| Reflectivity type | \( r_s \) | \( r_{cd} \) | \( f \) |
|------------------|----------|----------|------|
| Specular         | 1.64     | 1.769    | 1.5204 |
| Isotropic        | 3.60     | 8.294    | 1.5625 |

Table 6. The value of ‘f’ for the two reflectivities considered.
(c) The simulation will require extremely powerful computers in order to make the wave propagation simulation (instead of the geometrical optics one) on each and every feature of the reflective surface.

As regards the possibility to control the behaviour of the device, we may affirm that by changing the shape of it we may obtain different behaviours for a given type of reflectivity (specular, isotropic or lambertian). Moreover, taking into account the possibilities offered by different fabrication technologies, for example additive manufacturing (3D Printing), the device behaviour can be tuned to our will. For example, the cone-like part of the device may have the shape of half of an ellipsoid or any other geometry someone might envision. We can also tune the surface shape by adding various elements to it such as pyramids (either taping inside the device or recessed in the wall) or other such shapes. Moreover, we may consider apertures that do not ‘see’ each other (i.e. cannot be connected by a straight light ray), in which case a laser beam will also suffer asymmetric scattering when passing from one direction to other as compared to the reverse passing case.

The medium inside the device can be chosen at will. It may have various optical properties or, in the case of a transparent solid, can be built in such a way that have a refractive index that varies along the symmetry axis of the cone. Optical metamaterials may add further degrees of freedom, especially if they are non-reciprocal.

Since the palette of the device structures is so large, we will not present here all these cases.

The aspects mentioned above prove the versatility of the device presented by us.

Finally, one might ask whether this device is an optical diode or not. The device has no nonlinear element inside it so, according to [14], it wouldn’t be a diode. This is true, for the case presented above when laser light passing straightforwardly from one aperture to the other does not sense any diode effect. On the other hand, the strong asymmetry of the device is the factor that gives rise to asymmetric scattering for the two direction of propagation (direct and reverse). This asymmetry of scattering is the factor that offers, at least apparently, a diode-like character to the device. It must be noticed that, for each propagation direction, we always have the relation: \( R_d + T + A = 1 \), where \( R_d \) is the diode’s reflection coefficient as a device, \( T \) is its transmission and \( A \) is the overall absorption fraction of light. All these parameters depend on the number of reflections the rays experience inside the device. The geometrical asymmetry gives rise to different number of reflections and, thus, to different values for \( R_d \), \( T \) and \( A \) for the two counter-propagating beams. The quality of the device is influenced by the type of surface reflectivity. From the results presented above, for the same geometrical parameters, the isotropic scattering surface is the best one for obtaining the diode-like behaviour. The next one is the specular (smooth) surface while the Lambertian one does not prove to be of too great use. Changing the geometry and avoiding direct linesight from one aperture to the other (as mentioned above) change the overall behaviour and give indeed rise to a (very) asymmetric scattering for any type of light beam. Here, by any type of light beams we understand beams having any angular distribution. As can be seen from simulations presented, the diode-like behaviour depends strongly on the geometrical parameters of the structure (cone angle, aperture diameter) and the best/preferred transmission direction (left-to-right or right-to-left) may change depending on these parameters. A similar change occurs when varying the reflectivity type (specular versus the other two).

We considered that \( R = 0.99 \), i.e. \( R < 1 \). This means that there is a slight absorption of the light beam at each occurrence of a reflection process. Thus, we may assert that the difference not only in scattering but also in absorption (this being also caused by the asymmetrical geometry) contributes to the diode-like behaviour. The fact that overall absorption differs for the two counter-propagating beams—under identical entrance/exit apertures and light intensity distribution at input—may lead us to the idea that our device is a non-reciprocal one and this non-reciprocity is the factor that confers a diode-like behaviour to it. But linear absorption is known [21] to not giving rise to non-reciprocal behaviour. Another interesting aspect relies on the way short light pulses are temporally changed in an asymmetric manner when passing through the device. Suppose that the input radiation is chopped very fast so that short enough light pulses are applied at the entrance aperture. Because the rays, for the two opposite propagation directions, will travel different path lengths when reflecting onto the device inner walls (there is a different number of reflections between the two cases), the pulse duration will be slightly different when light is travelling from left-to-right than the case when travels into the opposite direction.

Our device is a linear and non-biased one. This means that it is a reciprocal device having an asymmetric behaviour. However, if the reflective surfaces are made of a magnetized material, then things change. The reflection on magnetized surface changes not only the intensity of the beam but also its polarization state. In this case, our device becomes a linear and biased one, being biased because of the presence of magnetization. Consequently, it acquires a non-reciprocal behaviour [21]. In such a case, we can rigorously call it an optical diode.

Finally, we do not use the term of ‘diode’ in the sense of rectifier. Rectification, at least in optics, takes place only in nonlinear systems and refers to the rectification of the electromagnetic wave inside a specific medium.
We use ‘diode’ here as a mean to show that the left-to-right and right-to-left transmissivities are asymmetric/unequal, similar to the case of electric current in electronic diodes. However, we have used above the term of ‘rectification factor’ just for naming the quantity that describes the asymmetrical behaviour of our device.

5. Conclusions

We have presented a novel concept of optical diode-like device for broadband, natural diffuse light that makes use of the scattering asymmetry inside the device. This asymmetry, stemming from the geometric one, alters the transmission and absorption between the two counterpropagating beams. If the reflective surface is magnetized material (ex. metal), then the device becomes non-reciprocal and can be considered an optical diode. This demonstrates its versatility that, combined with the very large spectrum, it makes it attractive for applications. The device behaviour is strongly dependent on the reflectivity type (specular, isotropic and, respectively, Lambertian) of the surface. The best results are obtained for the case of isotropic reflection. The conical geometry considered above was optimized as regards cone angle and aperture diameter for each of the three types of reflectivity considered. By serially connecting two such diodes the rectification factor is improved substantially. The device is extremely versatile allowing the tuning of the behaviour according to the needs, its behaviour being controlled not only by the geometry of it and the topography of the reflective surfaces, but also by the optical properties of the material that is placed inside it.

Acknowledgments

The work was performed under the framework of the Structural Funds contract No. 77/2016 ‘Parteneriat in exploatarea Tehnologiilor Generice Esentiale (TGE), utilizând o PLATFORMă de interacțiune cu întreprinderile competitive (TGE-PLAT)’, Cod MySMIS 105623, sub-contract 77.5D - Sistem optic formator de imagine folosind componente ‘freeform’ (FF) și tehnologie de realizare a acestora, POC-A1-A1.2.3-G-2-15 1.2.3. Parteneriat pentru transfer de cunoștințe.

Authors’ contribution

G.M.P. devised the devices and led the work. C.T. and D.V.U. performed the simulations. G.M.P. prepared the manuscript.

Annex

A1. Simulation details

We divided the entrance aperture into 500 equally spaced points. Each such point represents a light source that emits isotopically in all directions inside a cone whose tip angle is 179°. The number of rays in wave vector space is 750 (the number of rays emitted by each point). Therefore, a total of 375,000 rays were used in the 2D simulation. The rays inside such an emission cone are equally distributed from an angular point of view. Summation of intensity from all these sources is made in a non-coherent (i.e. arithmetically, adding intensities instead of amplitudes) way, since natural light is non-coherent.

Simulations were also performed for different values of the reflectivity. The results showed that the rectification factor decreases with the decrease in reflectivity, the diode-like behaviour almost disappearing for values of \( R < 0.5 \). Moreover, the output power is diminished so much at such low reflectivities that it makes the device unpractical regardless of the propagation direction. Because of that, we have chosen a value \( R = 0.99 \), a value that can be reached in practice (ex. by metallization).

A1.1. Preliminary simulation for checking convergence. Initially, we have considered several hundreds of rays for computing output power and rectification factor. Then, we have increased the number of rays to determine their number at which output values remain practically constant, i.e. independent of the number of rays. This number was obtained as being 750 rays (see figure A1). To ensure a good accuracy, we have considered a number of 300,000 rays for simulations. We have neglected the rays whose intensity decreased by more than \( 10^4 \) times with respect to the initial one (this corresponds roughly to 1000 reflection steps for a ray). While \( R \) represents the
fraction of reflected light per single process of reflection, \((1-R)\) represents the absorbed light fraction for the same process.

A1.2. 2D versus 3D simulation. Secondly, since the device has a circular symmetry, we used both 2D and 3D simulations. The difference between 2D and 3D cases proved to be around few percent (5\%–10\% from case to case), the 3D case indicating better figures for output intensity and rectification factor. In order to use properly the computing resources, we used the 2D case when considering the full number of 300,000 rays. This was necessary since approaching the 3D case with such a number of rays proved to exceed the computation capabilities at our disposal. Since the difference between 2D and 3D is not significant, we have chosen to increase
the number of rays in order to increase simulation accuracy. For 3D case we used 1,000, uniformly spaced, rays per release. Number of rays in wave vector space was taken equal to 1,000 (ray direction vector conical, uniform density). Thus, we used 2D simulations over the entire work. Not only the limited computing resources were a reason, but also the fact that the 2D case represents a ‘worst-case’ scenario when compared to 3D results. Proving the strong asymmetry even in such a (2D) case means that the 3D acts even better.

**A1.3. Full extent simulation.** The simulations were first performed for several \( \theta \) angles at an aperture diameter of 1 mm (the two opposed apertures have the same diameter). Then, by taking the angle value corresponding to the highest rectification factor, we varied the aperture diameter until further magnification of the rectification factor was achieved.

In all cases, the input power was considered as being equal to 1 unit.

The simulation results for the output power for the two opposed propagation directions as a function of the cone angle are presented in table A1.

What is interesting to note for isotropic and Lambertian cases is the fact that, compared to specular reflection, the rectification is achieved for the opposite direction. In other words, the optical diode transmits better from left to right in the case of specular reflection while the better transmission direction for isotropic reflection is from right to left.

It is observed from table A1 that the specular and Lambertian cases have left-right and, respectively, right-left transmissivities that are close to each other. Hence, it is expected that their rectification factor will be lower than for the isotropic case.

The simulation results regarding the radial intensity distribution for the two opposed propagation directions as a function of the cone angle are presented in table A2. We underline the fact that the input intensity distribution is uniform (top-hat) for all cases.
Within the simulation accuracy, the distribution intensity is quite uniform for the specular and lambertian cases, respectively. As regards the isotropic case, a strong non-uniformity is seen for the right-to-left situation, while the opposite one is also quite uniform as regards intensity distribution. However, the distribution intensity is strongly departed from the input top-hat one for all cases, behaviour that is given by the multiple scatterings taking place inside the device.

For the angle values mentioned in table 2 of the main text, we have studied the dependence of rectification on aperture diameter. The results are presented in tables A3 and A4. Again, the input intensity distribution is uniform (top-hat) for all cases. We mention that we preserved the number of pointlike light sources as in the case of initial simulation (dependence on cone angle).

The most important enhancement is seen for the isotropic case. In all cases, the transmission curve versus diameter can be very accurately approximated with a linear relationship.

As expected, table A3 shows that the output power increases with increasing aperture diameter. This happens because more light reaches to the exit aperture, either directly (i.e. without any reflection) or after a smaller number of reflections as compared to the case of small aperture. This also indicates a reduction of radiation loss in the device since less reflections means less losses.

As regards table A4, the radial intensity distribution is less uniform as compared to table A2. This is because the number of reflections/scatterings is reduced when the aperture is larger, giving rise to less homogenization of the beam at the exit. As is noticed from figures in table A4, the homogenization of intensity is dependent also on the propagation direction. Here, we speak about the homogenization of the part of the incident beam that is experiencing reflections.

Table A3. The output power for the two opposed propagation directions as a function of aperture diameter.
Table A4. The radial intensity distribution for the exiting beam (for the enhanced value of the maximum rectification factor) – Input intensity $= 1$ W mm$^{-2}$.

ORCID iDs

Gabriel Moaqr-Poladian encilhttps://orcid.org/0000-0002-0582-1014

References

[1] Kim M, Yao K, Yoon G, Kim I, Liu Y and Rho J 2017 A broadband optical diode for linearly polarized light using symmetry-breaking metamaterials Adv. Optical Mater. 5 1700600
[2] Fan L, Wang J, Varghese L T, Shen H, Niu B, Xuan Y, Weiner A M and Qi M 2012 An all-silicon passive optical diode Science 335 447
[3] Shiju E, Bharat M, Siji Narendran N K, Narayana Rao D and Chandrasekharan K 2020 Optical diode activity in an axially asymmetric nonlinear medium incorporated with phenothiazine and silver nanoparticles Opt. Mater. 99 109557
[4] Palikaras G and Kallos T 2013 Optical diode UK GB2514993 A
[5] Takezoe H, Park B, Song M H, Hwang J, Toyoooka T and Nishimura S 2007 Optical diode US Patent US 7, 701,537
[6] Manipatruni S, Robinson J T and Lipson M 2009 Optical nonreciprocity in optomechanical structures Phys. Rev. Lett. 102 213903
[7] Hafezi M and Rabl P 2012 Optomechanically induced non-reciprocity in microring resonators Opt. Express 20 7672
[8] Tocci M D, Bloemer M J, Scalora M, Dowling J P and Bowden C M 1995 Thin film nonlinear optical diode Appl. Phys. Lett. 66 2324
[9] Fan L, Wang J, Varghese L T, Shen H, Niu B, Xuan Y I, Weiner A M and Qi M 2012 An all-silicon passive optical diode Science 335 447–50
[10] Alberucci A and Assanto G 2008 All-optical isolation by directional coupling Opt. Lett. 33 1641–3
[11] Konotop V V and Kuzmiak V 2002 Nonreciprocal frequency doubler of electromagnetic waves based on a photonic crystal Phys. Rev. B 66 235208
[12] Hwang J, Song M H, Park B O, Nishimura S, Toyoooka T, Wu J W, Takanishi Y, Ishikawa K and Takezoe H 2005 Electro-tunable optical diode based on photonic bandgap liquid-crystal heterojunctions Nat. Mater. 4 383–7
[13] Li N and Ren J 2015 Non-reciprocal geometric wave diode by engineering asymmetric shapes of nonlinear materials Sci. Rep. 4 6228
[14] Jala D et al 2013 What is—and what is not—an optical isolator Nat. Photonics 7 579–82
[15] Zhu Z, Joshi S, Grover S and Moddel G 2013 Geometric diodes for optical rectennas ed G Moddel and S Grover Rectenna Solar Cells (New York, NY: Springer)
[16] El-Araby H A, El-Azem Malhat H A and Zainud-Deen S H 2018 Nanoantenna with geometric diode for energy harvesting Wirel. Pers. Commun. 99 941–52
[17] Moddel G 2009 Geometric diode, applications and method US8803340
[18] Moddel G, Zhu Z, Grover S and Joshi S 2012 Ultrahigh speed graphene diode with reversible polarity Solid State Commun. 152 1842–5
[19] Shin J H, Yang J H, Heo S J and Jang J E 2017 Geometric effect in a vertical stack-up metal-insulator-metal tunnel diode AIP Adv. 7 105307
[20] Zhang J, Brownless J and Song A 2019 Graphene bridge rectifier based on self-switching diode arrays Nanotechnology 30 364004
[21] Caloz C et al 2018 What is non-reciprocity? Phys. Rev. Applied 10 047001