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Probing the nano-scale with the symmetries of light

Xavier Zambrana-Puyalto[1,2*]
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[1] Department of Physics and Astronomy, Macquarie University, 2109 NSW, Australia
[2] ARC Center of Excellence for Engineered Quantum Systems, Macquarie University, 2109 NSW, Australia

* Corresponding author.
E-mail: xavierzambrana@gmail.com

Abstract

An alternative approach to study light-matter interactions in nano-photonics is presented. This method is based on considering light and sample as a whole system and exploiting their symmetries. The mathematical formalism to systematically study symmetries of light beams is explained and particularly applied to vortex beams. Then, the method is used in two different problems. First, it is shown that vortex beams can be used to effectively turn any dielectric sphere into a dual material. Then, it is seen that the same light beams can be used to excite whispering gallery modes on free space, thus avoiding the evanescent coupling typically used in these kinds of problems.

Introduction

In 1959, Richard Feynman gave a seminal lecture entitled "There's Plenty of Room at the Bottom" which pushed scientists to set out on the journey of controlling light-matter interactions at the nano-scale (Feynman, 1960). Since then, nanotechnology has rapidly developed. Nowadays it is unconceivable to think of any new information devices whose circuits are not nano-metric. Whereas nanoelectronics is a well consolidated technology producing transistors of less than 30 nm, nanophotonics has yet to overcome some drawbacks to be fully competent. One of the most important ones is overcoming the diffraction limit of light. Most of the efforts in this direction have been happening in the field of plasmonics. In fact, lots of authors consider that nanophotonics should be based on metallic nano-plasmonics (Brongersma, 2010). Plasmonics is the science that studies the interaction between light and free electrons on a metal (Maier, 2007). The first theoretical studies in plasmonics were done in the 1950's (Bohm, 1951; Pines, 1952; Bohm, 1953; Ritchie, 1957), and the first experimental realisations in the 1970's (Otto, 1968; Kretschmann, 1971). Since then, the field has successfully expanded and nowadays its applications have spread over many different fields (Lakowicz, 2006; Atwater, 2010; Juan, 2011). In general, plasmonics uses a sample-based perspective to overcome the diffraction limit of light. That is, given a fixed incident beam, samples are engineered (shape and materials) so that the desired light-matter interaction takes place. Fig. 1 shows the intensity profile of a typical incident beam used to excite plasmonic structures. A beam of light with such intensity profile is known as Gaussian beam, since its intensity profile can be described with a 2-dimensional Gaussian function (Pampaloni 2004). Now, there is no doubt that precise fabrication and characterization of samples play a huge role in designing the current plasmonic technologies. Interestingly, the spatial profile of the incident beam is also a key factor in the light-matter interaction.

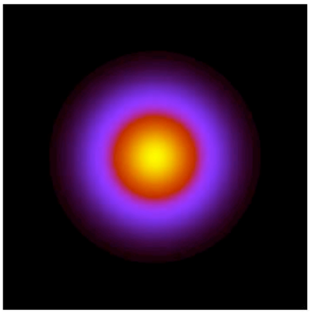

Figure 1: Intensity profile of a Gaussian beam. The intensity is maximum in the areas coloured in yellow, and minimum in those coloured in black.

However, most of the work in the field is done with Gaussian beams or plane waves. In this article, it will be shown that more elaborated beams of light can be used to retrieve plenty of additional information from nano-structures. An illustrative example is the Stimulated Emission Depletion (STED) microscopy. STED microscopy was invented by Stefan Hell and co-workers in 1994 (Hell, 1994). It is one of the so-called super-resolution microscopy methods, as it can resolve defects as tiny as 30nm (Rankin, 2009; Rittweger, 2009). Its working principle is detailed in Hell (1994, 2007), but the main idea is the following one. Probing a sub-wavelength specimen with a Gaussian beam results in a blurry image. Nevertheless, the combined use of a Gaussian and a doughnut-shaped beam results in a much neater image. That is, the use of a doughnut beam turns out to be crucial in order to overcome the diffraction limit of light. There are different kinds of doughnut-shaped beams, but the ones used in STED are called vortex beams (Molina-Terriza, 2007; Yao, 2011). Vortex beams are defined by their optical charge l, which is an integer number. The optical charge l accounts for the number of times that the phase of the beam wraps around its centre in a 2π circle. As an example, four different vortex beams are shown in Fig. 2. It can be seen that when $l = -1$, the phase goes from 0 to 2π one time in counter-clockwise direction. In contrast, when $l = 3$, the phase goes three times from 0 to 2π in a clockwise direction. Currently, vortex beams are mostly experimentally generated with Spatial Light Modulators (SLMs). Check Bowman (2011) and references therein to see how vortex beams are generated and what their principal applications are.

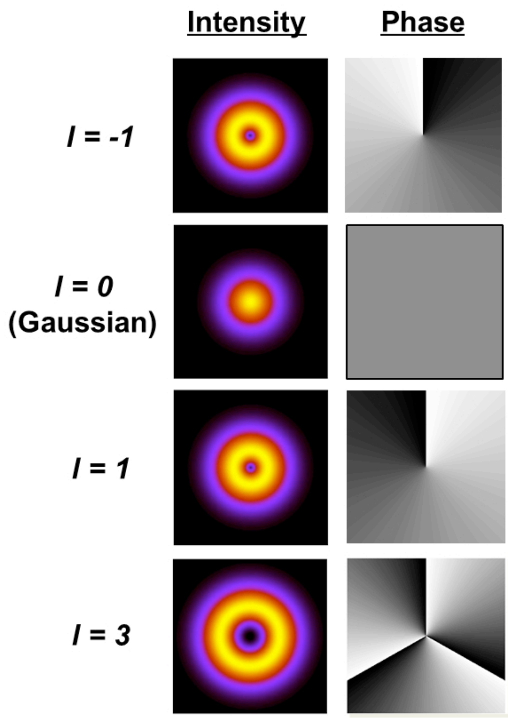

Figure 2: Intensity and phase profiles of vortex beams with optical charges $l = -1, 0, 1, 3$ respectively. For the intensity plots, yellow indicates maximum and black minimum. For the phase, white means 0 phase, and black means 2π.

Note that the definition of a vortex beam and its optical charge are independent of the polarisation. However, for many applications in nano-photonics (STED microscopy is one of them), vortex beams need to be tightly focused. When that is the case, vortex beams become much more complex. In fact, in that regime, the definition of the phase singularity is polarisation-dependent. This is what many authors have called spin-to-orbit conversion (Zhao, 2007; Vuong, 2010; Rodriguez-Herrera, 2010; Bliokh, 2010). Then, characterising vortex beams in terms of their symmetries becomes enormously useful. It allows for a systematic study of the beam without the need of considering different focusing regimes (paraxial or non-paraxial). Next, the bases to systematically characterise the symmetries under which a beam is invariant are given. Then, a general method to design structures using the spatial properties of light is sketched. Finally, two examples of the method are given. Firstly, it is shown that dielectric spheres can behave as dual materials for certain ranges of parameters. Furthermore, the role that the angular momentum of light plays in this process is unveiled. Secondly, it is shown that Whispering Gallery Modes (WGMs) can be excited on dielectric spheres without the need of evanescent coupling.

Vortex beams and symmetries

A vortex beam can be described with the following expression:

$$\overrightarrow{E_{l,p}}(\rho,\phi,z) = A_{\rho,l}\exp\left[\frac{-\rho^2}{w_0^2}\right]e^{il\phi}e^{ikz}\overrightarrow{e_p} \quad (1)$$

where (ρ,ϕ,z) are the cylindrical coordinates, $A_{\rho,l}$ is a normalisation constant, w_0 is the beam waist, l is the charge of the vortex, k is the wavenumber, and

$$\vec{e}_p = \left(\vec{x} + ip\vec{y}\right)/\sqrt{2} \quad (2)$$

is a circularly polarised vector, with $p=\pm 1$, for left (+) and right (-) circular polarisations respectively. A harmonic $e^{-i\omega t}$ is assumed throughout the remaining part of the article. The beam in Eq. (1) is a solution of the paraxial equation (Lax, 1975). Its intensity and phase can be described with the plots on Fig. 2 for the corresponding l's. Now, the first thing that one notices is that both the intensity and phase are symmetric under translations along the z axis. Mathematically, it means that $E_{l,p}$ is an eigenstate of T_z, the translation operator. In fact, using Noether's theorem (Noether, 1918) and group theory (Tung, 1985), it can be proven that $E_{l,p}$ must also be an eigenstate of P_z, the linear momentum along the z axis, as it is the generator of linear translations:

$$P_z\left[\overrightarrow{E_{l,p}}\right] = k\overrightarrow{E_{l,p}} \quad (3)$$

where k can be identified with the (eigen)value of P_z. Despite being less intuitive, it can also be proven that $E_{l,p}$ is symmetric (*i.e.* it is an eigenstate) under rotations around the z axis. Now, because the angular momentum is the generator of rotations, the following relation holds:

$$J_z\left[\overrightarrow{E_{l,p}}\right] = (l+p)\overrightarrow{E_{l,p}} \quad (4)$$

With $(l+p)$ being the (eigen)value of the angular momentum. Finally, it can also be proven that $E_{l,p}$ is symmetric under generalised duality transformations (Jackson, 1998). Then, because the helicity operator is the generator of duality transformations (Calkin, 1965), the following equation holds in the paraxial approximation:

$$\Lambda\left[\overrightarrow{E_{l,p}}\right] = p\overrightarrow{E_{l,p}} \quad (5)$$

where p is the (eigen)value of helicity. Now, there are different ways of mathematically describing non-paraxial vortex beams. One of the approaches is using the aplanatic model of a lens (Novotny, 2006) to compute the non-paraxial expression (Bliokh, 2011). Here, the symmetric properties of vortex beams will be exploited to compute their non-paraxial expression in a straight-forward manner. In order to do that, $E_{l,p}$ are expanded as a general superposition of Bessel beams $B_{p,m,k}$. Bessel beams are a general basis of solutions of Maxwell equations. That is, any field fulfilling Maxwell equations can be decomposed as a superposition of Bessel beams. They are also eigenstates of P_z, J_z, Λ, therefore, they can be used to describe $E_{l,p}$ in the paraxial approximation:

$$\overrightarrow{E_{l,p}} = \int a_k \vec{B}_{p,m,k} dk \quad (6)$$

where $m=l+p$, and a_k are some coefficients that modulate the superposition and depend on how tightly the vortex beam is focused. The general expression of Bessel beams, as well as their paraxial approximation can be found in Fernandez-Corbaton (2012). Note that due to the fact that both $E_{l,p}$ and $B_{p,m,k}$ are eigenstates of J_z, Λ, only a 1-dimensional integral has been needed. In the next sections, the symmetries of these beams will be exploited to demonstrate some effects which are unachievable with Gaussian beams (or plane waves).

Scattering control

As mentioned in the introduction, the typical approach to design nano-circuits or nano-materials it the following one. The nano-structure is characterized by its scattering matrix S. This scattering matrix is a function of many geometrical and material properties of the system, $S(g,m)$ where g and m are general sets of variables describing the geometrical and material properties of the structure. $S(g,m)$ is independent of the excitation beam. Then, the response of the structure to an incoming field E^{in} can be cast as a convolution of $S(g,m)$ with E^{in}:

$$\overrightarrow{E^{out}}(\vec{r}) = \left(S(g,m) * \vec{E}^{in}\right)(\vec{r}) \quad (7)$$

Since the properties of the structure do not depend on E^{in} and the incoming field is well-known (a Gaussian beam or a plane wave), the light-matter interaction is reduced to a complete characterization of the scattering matrix $S(g,m)$. Then, adjusting the geometry or material of the structure, a controlled interaction can be carried out. Nevertheless, this process is computationally expensive. Symmetries can be used to get around this problem. Instead, a highly symmetric structure whose scattering matrix is well-known can be chosen as the structure. Now, given this limitation, the sought interaction can be obtained by modifying the plane wave content of the excitation beam in a controlled manner. That is, instead of controlling E^{out} with the geometry and materials of the structure, the interaction is controlled with the incoming field E^{in}:

$$\overrightarrow{E^{out}}(\vec{r}) = \int d^3\vec{k}_i \exp(i\vec{k}_i \cdot \vec{r})\left(S(g,m) * \vec{E}^{in}(\vec{k}_i)\right)(\vec{r}) \quad (8)$$

where $\boldsymbol{k}_i$ are each of the different plane waves that take part in the superposition, and $E^{in}(\boldsymbol{k}_i)$ is the Fourier transform of the incident field, which modulates the plane wave decomposition. Symmetries play a double role here. First, they simplify the scattering matrix of the structure. Second, they bind the values that E^{out} can take. That is, when the symmetries of E^{in} are matched with the symmetries of the sample, then E^{out} must preserve the symmetries of E^{in}. For example, if the sample is cylindrically symmetric and E^{in} is a Bessel mode $B_{p,m,k}$, then E^{out} will have the same J_z value:

$$\overrightarrow{E^{out}}(\vec{r}) = \int dk' \left(a_{k',p}\vec{B}_{p,m,k'} + a_{k',-p}\vec{B}_{-p,m,k'}\right) \quad (9)$$

but in in principle the helicity value p could change and also new k components could be created. Next, two applications of this conceptual method are given. First, it is shown that a non-dual material can be turned effectively into a dual one if the proper vortex beam is chosen as illumination. Secondly, it is seen that vortex beams can excite WGMs, without the need of any evanescent coupling.

Inducing dual behaviour

A dual material can be defined as a material that preserves helicity upon scattering (Fernandez-Corbaton, 2013a; Zambrana-Puyalto, 2013c). The definition stems from the fact that helicity is the generator of generalized duality transformations. Recently, it has been proven that such a macroscopical material can only exist if the electric permittivity and magnetic permeability of all its subparts have a constant ratio (Fernandez-Corbaton, 2013a):

$$\frac{\varepsilon_i}{\mu_i} = const. \tag{10}$$

Interestingly, the microscopic Maxwell equations are not symmetric under duality transformations, as there are no magnetic monopoles in the universe. However, in the macroscopic approximation, Eq. (10) is enough to grant the material with a dual behaviour. Dual materials are useful for many different applications. They can be used to reduce the backscattering of samples (Fernandez-Corbaton, 2013a; Zambrana-Puyalto, 2013b), to create perfect optical rotators (Fernandez-Corbaton, 2013b), or to scatter light without changing the polarisation (Fernandez-Corbaton, 2013a), among others. Nevertheless, Eq. (10) is still very restrictive, and some other approximations can be done.

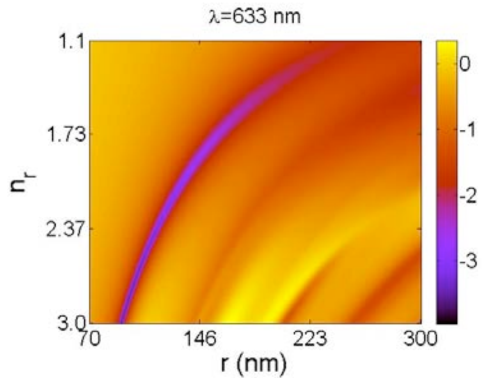

Figure 3: Plot of log|$T_p(r,n_r)$| as a function of r and n_r. The purple curve indicates the combination of parameters for which the sphere is dual. The incident field is a Gaussian beam with a wavelength of $\lambda = 633$nm.

It was analytically proven in Zambrana-Puyalto (2013c) that if certain combinations of $\{r, \lambda, n_r\}$ are used, non-dual dielectric dipolar particles can behave as dual under a Gaussian excitation. r is the radius of the sphere, λ is the wavelength of the excitation, and n_r is the relative refractive index of the particle with respect to the medium surrounding it. This phenomenon is summarised in Fig. 3. A Gaussian beam excites a sphere at $\lambda = 633$nm and the scattering is split into its two helicity components. Then, the component with the same helicity as the incident light is divided over the opposite one. This defines an adimensional transfer function $T_p(r,n_r)$, and its logarithm is depicted in Fig. 3. When log|$T_p(r,n_r)$| → −∞, then the sphere behaves as dual. As it can be seen in the horizontal axis of Fig. 3, the sphere is indeed dipolar (its size is much smaller than the wavelength). In fact, the same results have been experimentally demonstrated very recently by Geffrin (2012), Fu (2013) and Person (2013).

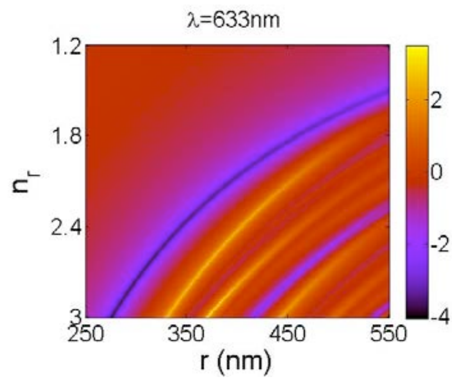

Figure 4: Plot of log|$T_p(r,n_r)$| as a function of r and n_r. The incident field is a vortex beam $E_{l=4,p=1}$ at $\lambda = 633$nm. Again, the purple curves indicate the parameters for which the sphere is dual. Note that the size of the sphere is not dipolar in this case, as r varies from 250 to 550nm.

Now, vortex beams can be used to extend this behaviour to particles of any size. The idea is that even though the particle gets bigger, the scattering of the first multipolar orders can be cancelled by chosing the corresponding vortex beam. In Fig. 4, a vortex beam $E_{l=4,p=1}$ is used, and as a consequence particle of almost 1 μm of size can behave as dual. Clearly, the choice of a vortex beam simplifies the problem. It would be much more complex to design a metamaterial of that size with similar features.

Excitation of Whispering Gallery Modes

Whispering Gallery Modes (WGMs) are widely used in physics. Their incredibly high Q factors make them perform very well to probe any sort of disturbance in the environment (Schiller, 1991; Oraevsky, 2002; Vahala, 2003). Also, they can be used in quantum information processes, such as quantum optomechanics (Lee, 2010; Forstner, 2012). In Oraevsky (2002), it is demonstrated that a plane wave cannot excite a WGM. Instead, an evanescent wave must be used to excite one of these modes. WGMs are actually modes of light with very large value of J_z, of the order of 1000 occasionally (Schiller, 1991; Oraevsky, 2002). An alternative way of exciting WGMs without the need of using fibers or prism to create evanescent waves is sketched here. It is based on the fact that spheres are symmetric under rotations around the z axis. Thus, if a sphere is excited with a vortex beam with a large value of J_z, the scattered field must preserve that large number of J_z (Zambrana-Puyalto, 2012; Zambrana-Puyalto, 2013a). However, the incident beam must fulfil another condition in order to excite a WGM with a high Q factor. The Q factor of the mode drastically depends on the coupling between the incident beam and the sphere. This coupling is modelled by the so-called Mie coefficients (Bohren, 1983). In order to ensure a good overlap between the incident vortex beam and the WGM, the following condition between $\{r, \lambda, n_r\}$ needs to be fulfilled (Zambrana-Puyalto, 2012; Zambrana-Puyalto, 2013c):

$$r \approx \frac{m\lambda f(n_r)}{2\pi} \qquad (11)$$

where m is the value of J_z of the WGM, and $f(n_r)$ is a function of the relative refractive index that can be calculated (Zambrana-Puyalto, 2013c). When both conditions are fulfilled, a high-Q WGM can be excited with a vortex beam, without the need of carrying out any evanescent coupling.

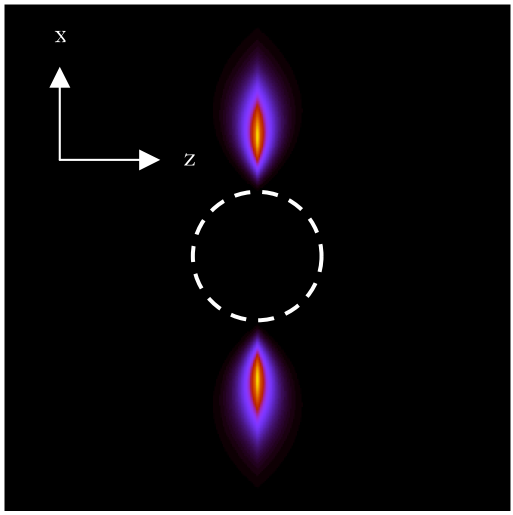

Figure 5: Intensity plot of a scattered WGM of order $m=15$. Yellow means maximum intensity, and black minimum. The dashed circle depicts the position of the sphere. In order to obtain such a scattered field, an incident vortex beam $E_{l=14,p=1}$ propagating in the z axis has been used. The excitation is at $\lambda = 633$nm, and the particle is made of a material such that $n_r=1.5$, which implies that $f(n_r)=0.8$ (Zambrana-Puyalto, 2013c). Its radius is $r=1.2\,\mu m$.

Conclusions

It has been shown that the symmetries of light can be used to control the scattering of nano-structures. In particular, vortex beams, which can be symmetric under rotations, translations, and duality transformations, have been used to control two scattering events. Firstly, they have been used to induce duality symmetry in an arbitrary large dielectric non-dual sphere. And secondly, they have been used to excite WGMs without the need of using evanescent couplings.

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Xavier Zambrana-Puyalto is a PhD student at the Department of Physics&Astronomy, Macquarie University. He did his undergraduate studies in Spain, where he earned a B.Sc. Major in Physics by the University of Barcelona and also a B.Eng. Major in Civil Engineering at UPC BarcelonaTech. He then carried out a Masters in Civil Engineering, majoring in Numerical Methods for Engineering, also at UPC BarcelonaTech. Xavier joined Macquarie University in September 2010, under the guidance of A/Prof. Gabriel Molina-Terriza. His current interests lie in the field of nano-optics, plasmonics, and the uses of the angular momentum of light. Xavier was the Society's Jak Kelly award winner for 2013, awarded to the best student physics presentation at a joint meeting with the Australian Institute of Physics (AIP).