Switching of free space diffraction with a tailored PT symmetric grating

N. Rivolta,[1] B. Maes[1]

[1] Micro- and Nanophotonic Materials Group, Faculty of Science, University of Mons, 20, place du Parc, B-7000 Mons, Belgium

We numerically study the diffraction properties of a parity-time (PT) symmetric transmission grating. This kind of grating consists of a periodic structure with balanced real and imaginary parts of the refractive index. We tailor the geometry and phase of the structure to achieve high diffraction efficiencies in only two diffraction orders. The combination of gain and loss creates the PT symmetric behaviour: a critical, symmetry-breaking point is reached when the imaginary part is increased. The different characteristics around the critical point in our tailored grating are analyzed, and the device can function as an efficient switching device.

Introduction

In quantum physics, the Hamiltonian must be hermitian to ensure that the eigenvalues are real. But a weaker condition can also ensure this fact, this condition is called PT symmetry [1]. A new and wide range of Hamiltonians can be accessed and new physics can be described with this condition.

The similarity between the equations of optics and quantum physics allow us to apply this theoretical discovery in concrete optical structures with novel properties [2]. One of these new properties is the spontaneous symmetry breaking, a clear-cut transition between two regimes with very different behaviours.

Here we use the PT symmetric properties to transform a well known free space diffraction grating into a powerful switching device. To understand the phenomena in this grating, we use numerical simulations (eigenmode expansion with CAMFR and finite element method with COMSOL).

Diffraction grating

We design the geometry of the structure to achieve high diffraction efficiencies in only two diffraction orders [3]. The grating is a fused silica transmission grating with a period of 800 nm and a fill factor of 0.4. In the Littrow-mounting[1], the grating experiences only two guided modes (see the next section) each excited by half the input power. By adjusting the groove depth, the interference between the two modes allows us to transmit almost all the power to the 0 diffraction order or the -1 (Fig.1A).

[1] Incident and diffraction angles are identical. This means that the lateral component of the propagation constant of the incident wave is equal to π/period.

The novelty here lies in the small amount of gain/loss injected in the grating (Fig.1B). The refractive index in the grating is defined as $n(x) = n_r(x) + \Gamma\, n_i(x)i$, the real part n_r is symmetric relative to the period and the imaginary part n_i is antisymmetric. Therefore the whole grating is assured to respect the PT-symmetric condition. The amount of gain/loss injected is defined by Γ who is a real positive.

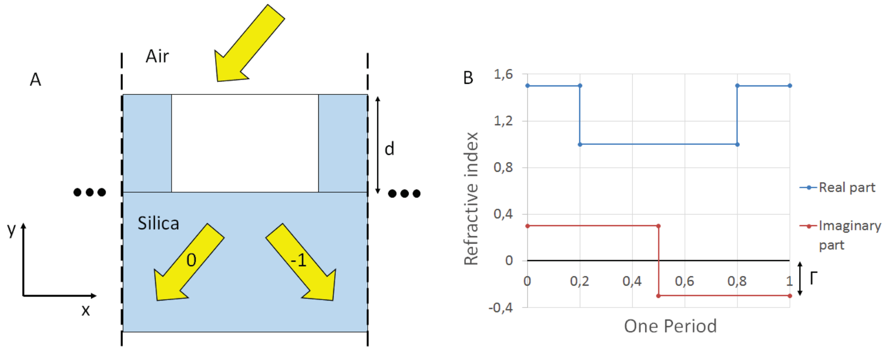

Figure 1: (A) One period of the grating and its substrate. Light is incident with the Littrow-mounting and is diffracted in only two diffraction modes. (B) Real and imaginary part of the index of refraction along one period of the grating. The shape remains fixed while the imaginary part will be increased in absolute value by a factor Γ.

The wavelength of the incident light is 1060 nm and the period is 800 nm. We have varied the groove depth (d) and Γ and we have measured the amount of power transmited in each diffraction channels (Fig.2).

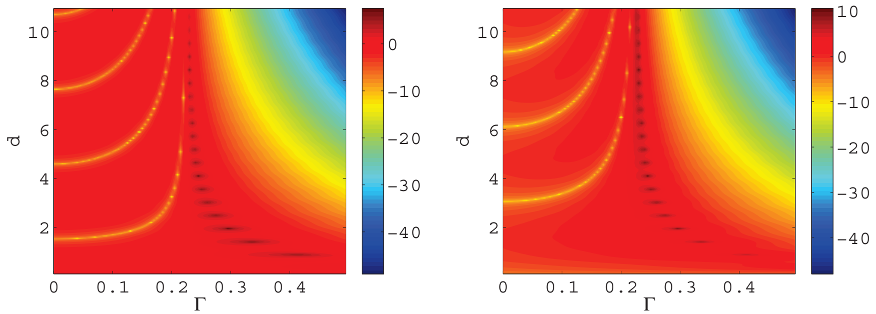

Figure 2: Transmited light to diffraction order 0 (left panel) and diffraction order -1(right panel). Γ is the absolute value of gain/loss injected in the grating and the two graphs are in log scale.

We clearly see two very different regimes on either side of $\Gamma = 0.23$. Beneath this point we have the usual behaviour, in function of the groove depth, the two guided mode interfere and allow the light to be transmited in the two different diffraction orders. For example for a groove depth of 6.1 μm and $\Gamma = 0$, all the light is transmitted to the order 0.

In this regime the structure can act like a very efficient switching device. Near the breaking point with a fixed groove depth, we can choose in which channel we want the light to be transmited with a very small gain/loss variation.

Beyond the breaking point, the behaviour is very different. We can see a laser effect on the islands with very large transmission and we can also see that the light can no longer be coupled to the two different diffraction orders.

Therefore we can transmit all the light in the desired diffraction order or transmit nothing simply with a gain/loss modulation.

Propagating modes

We can explain all the previous behaviours by analysing the effective refractive indices of the two modes that propagate in the grating. These effective refractive indices (Fig.3) are defined from the longitudinal component of the propagation constants of the propagating modes in the grating.

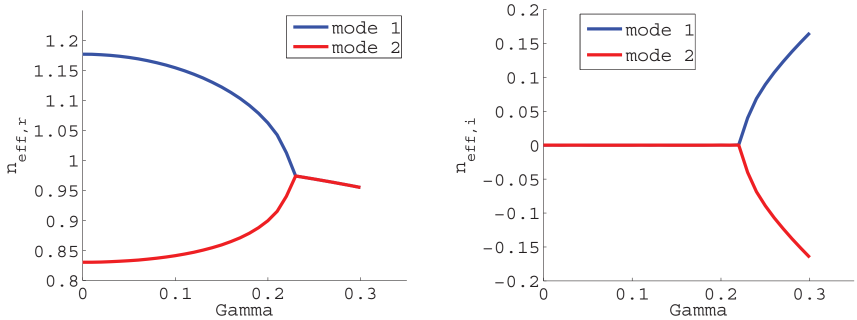

Figure 3: Real (left) and imaginary (right) part of the effective refractive indices of the two modes in function of Γ (the amount of gain/loss).

We clearly observe the PT-symmetry breaking point around $\Gamma = 0.23$. The real parts of the two modes merge while one mode experiences gain (positive imaginary part) and the other experiences loss beyond the critical point. It is now a well known phenomenon in the PT-symmetry field already described for an infinite grating [4].

Beneath the breaking point, the effective indices (i.e. the propagation constant) come close to each other. This means that the distance (i.e. the groove depth) needed for the two-mode interference increases. This explains in figure 2 why the groove depth needed to switch from one order to the other with fixed gain/loss increases closer to the breaking point.

Beyond the breaking point, the laser effect (the islands with very large transmission) are explained by the round trip of the mode that experiences gain with the formula: $e^{-i\,k_0\,n_{eff}\,2d} r_1 r_2 = 1$ (with d the groove depth, k_0 the propagation constant of the incident wave and r_1 and r_2 the mode reflection at the two interfaces).

Conclusion

With rigorous simulations we have analysed the behaviours of a PT symmetric diffraction grating. This structure experiences a PT symmetry breaking point when the gain/loss is increased. This point mark a clear boundary between two very different regimes.

Beneath this point, the interference between the two modes allows us to transmit all the light in the desired diffraction order. Beyond this point, the light is no longer coupled to the mode and diffracted. Moreover a laser effect can be achieved with a good set of groove depth and gain/loss.

Therefore, with a geometrically fixed structure, we can transmit all the light in the desired channel or transmit nothing with a moderate gain/loss modulation.

Acknowledgement

This work is supported by the Belgian Science Policy Office under the project "Photonics@be" (P7-35) and by the Fonds National de Recherche Scientifique (FNRS) in Belgium.

References

[1] C.M. Bender and S. Boettcher, "Real spectra in non-hermitian Hamiltonians having PT symmetry", *Physical Review Leters*, vol. 80, no. 24, pp. 5243-5246, 1998.

[2] T. Kottos, "Broken symmetry makes light work", *Optical Physics*, vol. 6, pp. 166-167, 2010.

[3] T. Clausnitzer, T. Kampfe, E.-B. Kley, A. Tunnermann, U. Peschel, A.V. Tishchenko and O. Parriaux, "An intelligible explanation of highly-efficient diffraction in deep dielectric rectangular transmission gratings", *Optics Express*, vol. 13, no. 26, pp. 10456, 2005.

[4] K. G. Makris, R. El-Ganainy, D. C. Christodoulides and Z. H. Musslimani, "PT-symmetric optical lattices", *Physical Review A*, vol. 81, no. 063807, 2010.