

## Chapter 2

# Coupling of Spontaneous Emitters with Bloch Surface Waves

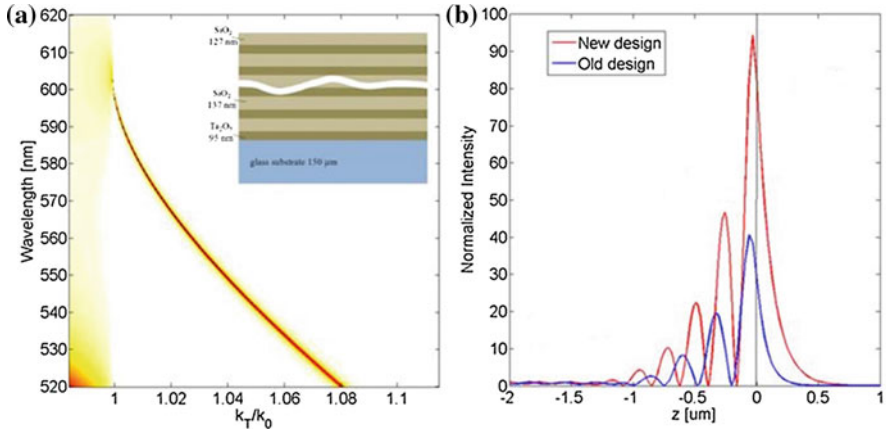
Since the pioneer work of Purcell [1], it has been clarified that the emitting properties of a light source can be strongly modified by the photonic environment surrounding it. According to the *Fermi's golden rule* applied to the decay properties of an emitter, both the emission rate and the direction of emission are affected by the Local Density of Optical States (LDOS) [2]. In analogy with the density of electronic states, the LDOS counts for the available electromagnetic modes in which photons can be radiated from a specific location.

In proximity with a Photonic Crystal (PC) structure the radiative properties of an emitter are modified according to the photonic band structure [3] of the PC. Because of Bragg's diffraction causing constructive and destructive interference along certain directions, the far-field radiation pattern turns out to be a strongly anisotropic pattern [4]. In the case of a 3DPC exhibiting a complete band gap for a given range of frequencies, the radiative decay can be completely inhibited [5].

The high directionality achieved by employing photonic crystals has found application in different fields such as biosensing [6] or quantum information [7]. As already mentioned in the first chapter, in a phenomenological picture BSW can be seen as the photonic counterpart of SPRs. A well-known effect occurring when an emitter lies in close proximity to a metallic surface is the so called Surface Plasmon Coupled Emission (SPCE) [8]. In this case a significant portion of light radiated couples to the SPPs. The emission pattern is therefore modified according to the dispersion relation of the SPPs.

As a consequence of an enhancement of the LDOS occurring at the interface of properly designed 1DPC, an effect similar to SPCE occurs when BSW are considered [9]. In this chapter, I will show that BSW-Coupled Emission (BSW-CE) can be exploited to obtain a highly directional fluorescent emission combining the advantages of using a surface mode instead of a buried photonic mode together with the intrinsic weak ohmic losses typical of dielectric materials.

The enhanced LDOS at the truncation interface of the multilayer modifies the emitting properties of a light source thereon located [10]. The elementary cell of the design proposed here is composed by a high index layer of  $Ta_2O_5$  ( $n_h = 2.08$  at  $\lambda = 600\text{ nm}$ ) and a low index layer of  $SiO_2$  ( $n_l = 1.45$  at  $\lambda = 600\text{ nm}$ ). The thicknesses



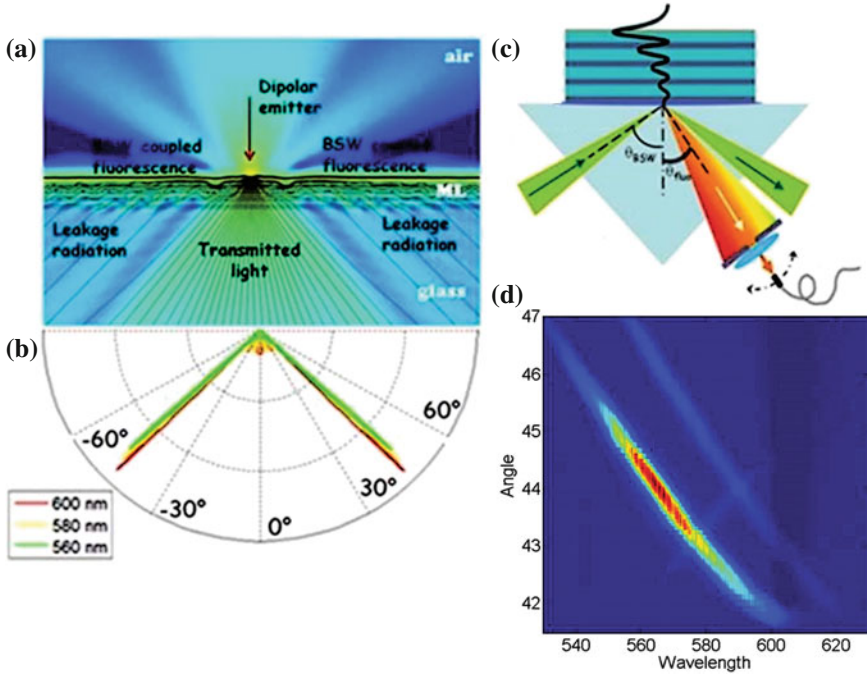
**Fig. 2.1** **a** Calculated TE reflectance map for the multilayer design sketched in the *inset*. **b** Calculated electric field distribution of the BSW along the multilayer cross-section. The *black line* indicates the truncation interface position. The intensity has been normalized with respect to the propagating radiation in the glass. The *red line* is associated to the BSW sustained by the design in (a), while the *blue one* is associated to the multilayer discussed in Chap. 1

are 95 nm and 137 nm respectively, whilst the last layer of  $\text{SiO}_2$  is 127 nm thick. We fabricated different samples with the same elementary cell and different number of layers, namely 8, 12 and 20 layers). The reflectance map of a multilayer with the same elementary cell and 12 layers (sketched in the inset) is reported in Fig. 2.1a. Figure 2.1b shows a comparison among the electric field distributions of the BSW modes associated to the multilayer design described in the previous chapter and the new one. As can be observed, the new design exhibits a higher enhancement of the LDOS at the truncation interface of the 1DPC, showing that the photonic properties of the sample can be tailored.

In order to evaluate the near-field coupling we modeled the field radiated by a point-like source (in the 2D model represented by an out-of-plane line of current) in a FEM model (Fig. 2.2a).

The modeling domain is a vertical cross-section of the multilayer and the emitter is placed 5 nm above the surface. The entire domain is surrounded by Perfectly Matched Layers (not shown in figure) so that boundary reflections are avoided and the domain resembles an open domain.

In order to have an effective coupling, a polarization matching between the radiated field and the BSW mode is required. The BSW is TE polarized, meaning that there are 2 possible orientations of the electric field, both matching the polarization of the BSW. We chose to have the electric field out of the plane of the cross section, in order to have the Poynting vector lying in the cross-section plane. The wavelength of the emitted radiation has been swept in the range from 560 to 600 nm (the image in Fig. 2.2a is taken at  $\lambda = 580$  nm).



**Fig. 2.2** **a** Cross sectional view of the calculated near-field distribution of the electric field radiated by a point like source. **b** Calculated far-field radiation pattern corresponding to the near-field distribution in (a) for different wavelengths. **c** Sketch of the experimental setup in the reverse Kretschmann configuration. Adapted from [10] **d** Experimental fluorescence intensity map function of  $(\lambda, \theta)$ . Adapted from [10]

The modeling result shows a cone of light radiated in air and one directly transmitted through the multilayer. Beside this, part of the energy couples to the BSW mode and propagates parallel to the truncation interface. The black continuous lines indicate the power flow. As long as the BSW-CE propagates at the multilayer interface, part of the energy tunnels through the multilayer and leaks into the substrate. According to the momentum conservation law, the leakage radiation propagates into the substrate at a specific angle determined by the BSW dispersion relation given by the following relation:

$$k_{BSW} = k_0 n_{sub} \sin(\theta_{BSW}) \quad (2.1)$$

where  $k_{BSW}$  is the BSW wavevector,  $k_0$  is the free-space wavevector,  $n_{sub}$  is the substrate refractive index (in our case  $n_{sub} = 1.5$ ) and  $\theta_{BSW}$  is the leaking angle.

Since BSW are characterized by a well-defined dispersion relation, different wavelengths will couple to BSW with a different wavevector, and will be therefore out-coupled at different angles. The far-field radiation pattern at different wavelengths has been computed (Fig. 2.2b) from the near-field distribution thanks to an algorithm

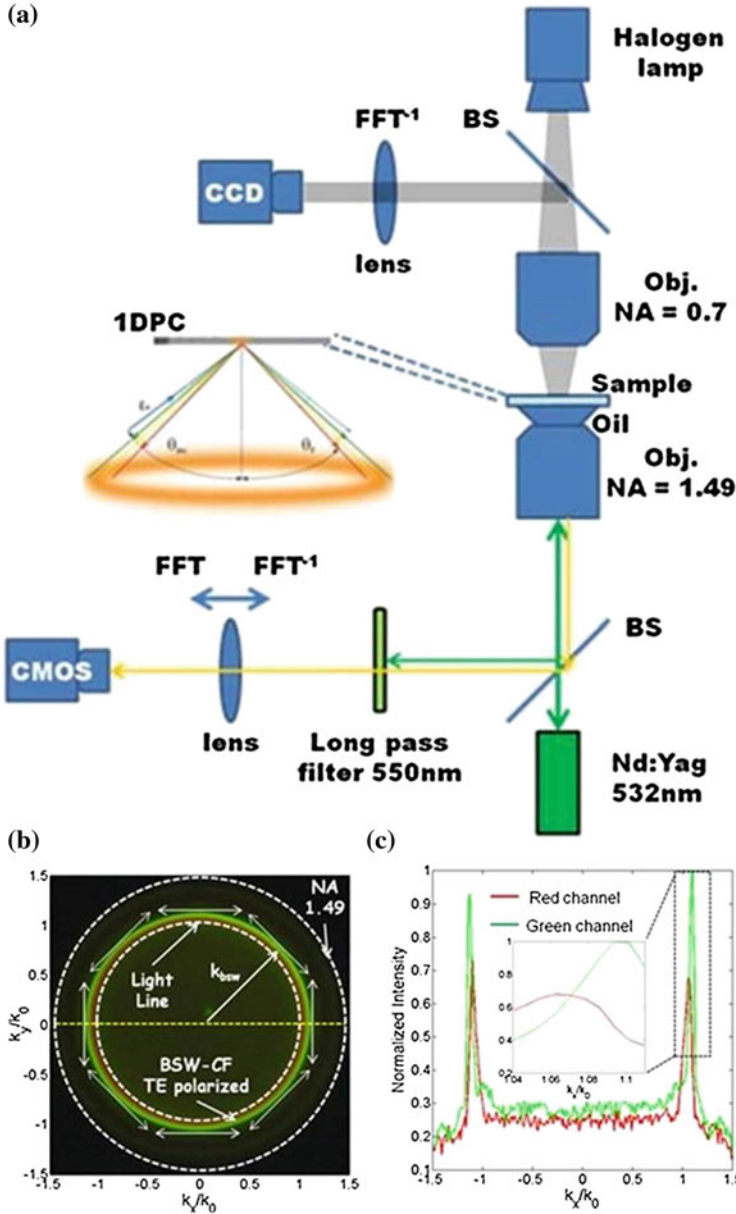
based on the surface equivalent theorem [11]. Three exemplary patterns at three different wavelengths are reported in the polar plot, where it is clearly visible a variation of the output angle. In detail, longer wavelengths correspond to smaller wavevector and therefore to smaller output angles.

By employing a reverse Kretschmann configuration it is possible to recover the BSW dispersion relation in fluorescence. In Fig. 2.2c is reported a sketch of the experimental setup (for details see for example *Ballarini et al., Appl. Phys. Lett.* 99, 043302). The optical coupling between the prism and the substrate hosting the multilayer allows for extract the BSW-CE. The collection arm consists of a low NA lens focusing light at the inlet of a multi-mode fiber connected to a spectrometer. Such configuration provides high angular resolution combined with spectral analysis. An homogeneous fluorescent layer covering the surface of the 1DPC is obtained by incubating a solution of protein A labeled with Alexa Fluor 546 (PtA Alexa 546) ( $1 \mu\text{g/ml}$ ) for 20 mins and rinsing it with PBS solution in order to remove the excess of protein. The measured map reported in Fig. 2.2d shows a bright band following the BSW dispersion relation that corresponds to the BSW-CE. In the inset an intensity profile extracted along the yellow band shows that a specific wavelength is radiated at a well defined angle with low divergence.

As an alternative way, leakage radiation can be efficiently collected by employing an high numerical aperture oil immersion objective. In order to evaluate the BSW-CE angular distribution, the experimental setup shown in Fig. 1.6 has been modified as depicted in Fig. 2.3a. Briefly, fluorescence on the surface of the 1DPC is excited with a collimated laser beam (Nd:Yag,  $\lambda = 532 \text{ nm}$ ) and imaged on the RGB CMOS camera after filtering out the excitation light with an edge filter (Semrock 532 nm RazorEdge). The adjustable tube lens in front of the CMOS camera allows to image both the direct plane and the BFP of the oil immersion objective [12]. Figure 2.3b shows an example of BFP imaged when fluorescence is excited on the flat surface of a 1DPC. The outer and inner dashed white circles indicate respectively the NA of the objective and the light line. The fluorescence ring lying right beyond the light line corresponds to the projection of the cone of emission resulting from the leakage of the BSW-CF, schematically depicted in Fig. 2.3a. The RGB image allows to qualitatively evaluate the BSW dispersion.

The fluorescence ring is characterized by an external green area that turns into red light approaching the light line. A cross-section of R and G channels along the yellow dashed line allows to better evaluate the dispersive behavior of BSW-CE and compare the experimental results to the theoretical predicted output angles. The normalized transverse wavevector ( $k_T/k_0 = n_{eff}$ ) associated to shorter wavelengths (green) of the spectrum has its maximum at 1.09, corresponding to an output angle of  $46.6^\circ$ , while the peak associated to longer wavelengths (yellow-red) is centered at  $n_{eff} = 1.05$  ( $44.4^\circ$ ). Such values can be compared to the angles of emission calculated for  $\lambda_G = 540 \text{ nm}$  and  $\lambda_R = 600 \text{ nm}$ , that are respectively  $46.5^\circ$  and  $44.5^\circ$ .

Due to the polarization selectivity of the BSW mode, only dipoles whose momentum is oriented parallel with the surface will efficiently couple with the BSW. As a consequence, BSW-CE will exhibit a well defined polarization as well, and it will be



**Fig. 2.3** **a** Schematic view of the customized fluorescence leakage radiation microscope. **b** Example of real color fluorescence BFP obtained when fluorescence is excited on the flat surface of a 1DPC. The external *white dashed ring* indicates the NA of the oil immersion objective, while the internal one signs the air/glass light line. The light polarization state is indicated by the *white arrows*. An intensity cross-section is reported in **(c)**, where the normalized intensities collected by the R and G channels of the CMOS camera are reported. In the *inset* a detail about the angular position of the two peaks

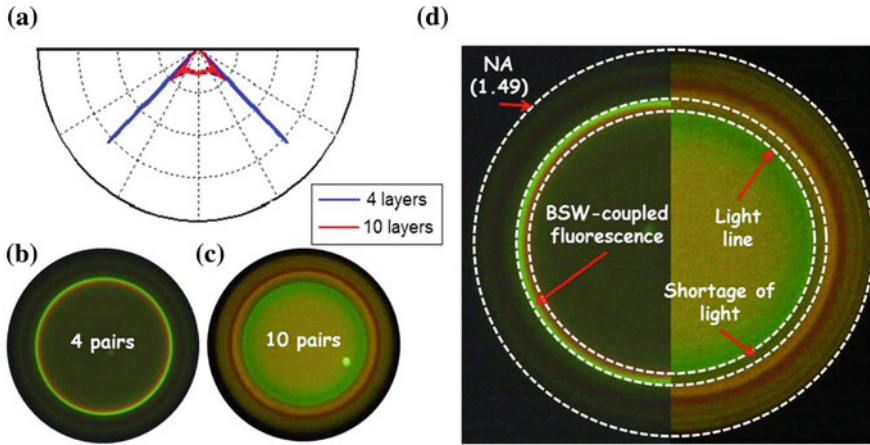
azimuthally polarized (see white arrows) in the specific case of TE polarized BSW (conversely, SPCE occurring on a flat metallic film is radially polarized, reflecting the TM nature of SPPs [13]).

## 2.1 Tunable Coupling of BSWs with the External Environment: Influence of the Multilayer Thickness

Several factors may contribute to reduce the quality factor of BSW. Defects on the surface as well as inhomogeneities of the multilayer stack may give rise to scattering of the radiation coupled to the mode. Ohmic losses can be also taken into account although their contribution is rather weak, especially in the visible range. Provided that the multilayer exhibits a reasonable optical quality and the materials are characterized by low intrinsic ohmic losses, the main channel draining energy out from the mode is the leakage of light through the multilayer. It is indeed the tunneling of light through the photonic structure that allows to collect the BSW-CE. The leakage of light into the substrate can be interpreted as a tunneling event due to the finiteness of the multilayer. By increasing the number of pairs composing the multilayer the tunneling event should be frustrated and leakage radiation suppressed. In other words, the coupling of the BSW mode with the far-field propagating substrate modes is reduced, and the energy exchange between the BSW mode and the external environment is inhibited. In order to confirm such prediction, we computed the radiation patterns of the point-like sources lying on the surface of two 1DPCs with same elementary cells but different number of layers. The numerical results are reported in the polar plots in Fig. 2.4a. By taking the amount of directly transmitted light as reference, we can observe that the two peaks in the substrate corresponding to the leakage radiation are suppressed when the *10 pairs* design is considered, meaning that the major part of fluorescence coupled to BSW has not been radiated in far field and it is still guided on the surface of the 1DPC at the boundaries of the modeling domain which is about 100  $\mu\text{m}$ .

Figure 2.4b and c show the fluorescent BFP collected when fluorescence is excited on the flat surface of a *4 pairs* (b) and *10 pairs* (c) 1DPCs (the two samples have the same elementary cell). The first image is dominated by the bright ring beyond the light line corresponding to the BSW-CE. The second one appears brighter because of a higher excitation intensity employed to put in evidence the photonic band structure in the BFP, confirmed by the much higher intensity of the directly transmitted light within the light line. At the angular position where the BSW-CE is expected to be, there is a shortage of light, indicating that BSW-CE does not leak anymore into the substrate and it is therefore no more collectable in far field.

In order to have an easier comparison, the images reported in (b) and (c) have been merged in a single image. The angular position of the BSW is characterized by a peak of fluorescence in the *4 pairs* design, while at the same position a shortage of light is observable when the *10 pairs* design is considered. Therefore, in the low leakage



**Fig. 2.4** Calculated far field radiation pattern for two multilayers with same design and four pairs of layers (blue line) and ten pairs of layers (red line). **b, c** Experimental fluorescence measure showing the BFP collected when fluorescence is excited on the flat area of a four pairs **b** and ten pairs **c** 1DPC. The two images are merged in **(d)** for easier comparison

design, we can assume that BSW-CE is forced to be confined at the surface and the main factor reducing the propagation length are the surface defects and ohmic losses of the layers, that are determined by the overall quality of the fabrication process.

The possibility of controlling the leakage radiation and eventually suppress it gives an interesting advantage in this framework: the interaction of fluorescence coupled to the surface modes with distributed surface structures can be indeed enhanced if competitive radiative decay channels are inhibited.

## 2.2 Directional Extraction of Luminescence Assisted by Surface Relief Gratings

The ability of controlling the directivity of spontaneous emission is an objective of outstanding relevance in a variety of fields dealing with fluorescent emitters, such as biosensing when labeled markers are employed [4] or quantum information applications based on transmission of single photons emitted by single photon sources [14]. The enhanced directionality of spontaneous emission would allow to enhance the collection efficiency of fluorescence by employing low numerical aperture systems that can operate also from the air side (and not necessarily from the substrate as in the case of oil-immersion optics).

A grating coupler can also be exploited to efficiently extract the BSW-CE into a collimated beam. Such effect has been widely reported when SPCE on a periodically corrugated metallic film is considered [15, 16]. Although an effective beam generation assisted by Surface Plasmons (SPs) has been reported by several groups, the performances of such systems are often limited by the typical decay lengths of

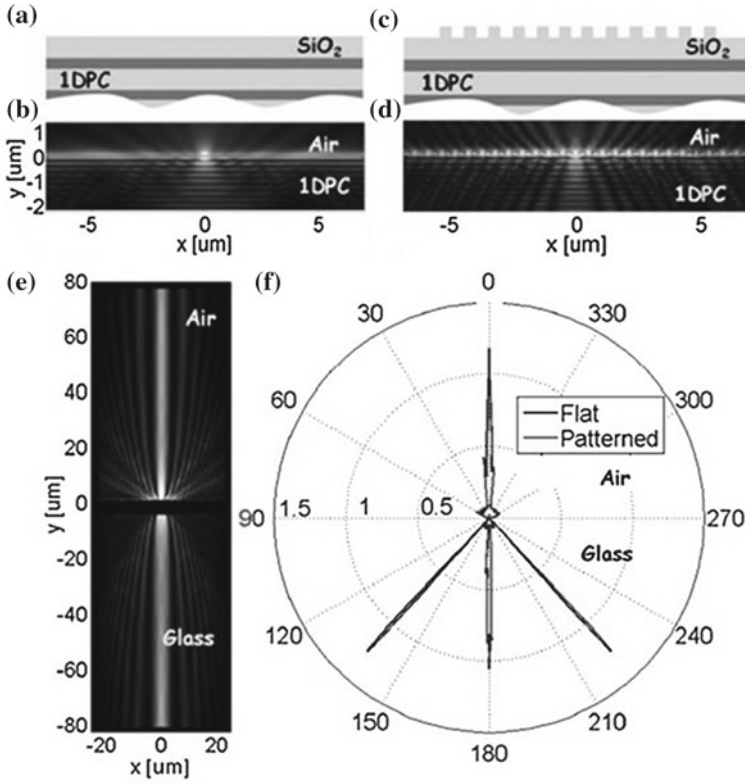
SPs that, in the visible range, do not exceed few tens of microns [17]. Moreover the directionality of emission is intrinsically limited by the broadness of SPs resonances, mainly due to ohmic losses. For the above mentioned reasons, we expect that longer decay length as well as a narrower resonances provided by the photonic crystal platform would allow for higher directionality of the extracted fluorescence.

The directional extraction of radiation coupled to resonant modes may be critical in some applications. The use of immersion optics or prisms to extract the leakage radiation might be limiting or unfeasible. As an example, the prism may impose a strong constrain when an image of the surface based on the leakage radiation is required [18], while the alignment of immersion optics may be not trivial. The use of relief gratings patterned on the surface of the 1DPC should allow to diffract energy coupled to BSW into free-space radiation by adding a specific momentum given by the grating periodicity, according to the Bragg's law.

In the following, we will consider a linear grating patterned on the surface of two 1DPC samples. The sequence of the multilayer stacks considered here is *glass-N[ $Ta_2O_5$  (95 nm)- $SiO_2$  (137 nm)]- $Ta_2O_5$  (95 nm)- $SiO_2$  (127 nm)-air*, where N can be 4 or 10 (see Chap. 1). Given the dispersion relation of the BSW, the Bragg's law can be used to determine the grating periodicity needed to normally diffract BSW-coupled emission, at least to a first approximation. It has to be noticed indeed that the fabrication of the grating modifies the dispersion relation of the BSW, because of the dielectric loading effect (Sect. 1.2).

In order to optimize the grating parameters (i.e. period and corrugation depth), the FEM model proposed in Chap. 1 (emitter on flat surface, Fig. 2.5a, b) has been modified by introducing a surface corrugation (Fig. 2.5c, d). In the model the diffractive structure has the same refractive index of  $SiO_2$  ( $n_{SiO_2} = 1.45$  at  $\lambda = 600$  nm). The grating parameters were optimized in order to have a normally diffracted beam at  $\lambda = 570$  nm, i.e. the peak emission wavelength of PtA Alexa 546 which is the fluorescent probe used in the experimental observations. The parametric study over the diffraction efficiency as a function of the corrugation height indicates that the maximum efficiency occurs when the grating height is about 80 nm (calculations not shown), while the periodicity needed to normally diffract BSW-CE at  $\lambda = 570$  nm is  $\Lambda_g = 520$  nm. The near field distribution (Fig. 2.5d) shows that fluorescence radiated couples with the surface modes and undergoes scattering events as long as it propagates parallel to the truncation interface. By enlarging the simulation domain (Fig. 2.5c), far from the surface it is visible the formation of a normal beam due to the coherent superposition of the scattered light. By computing the far-field pattern (Fig. 2.5d), a pronounced normal beam is generated both in air and in the substrate, while the two lateral beams associated to leakage radiation of BSW-CF on a flat surface (number of layer pairs  $N = 4$ ) (here reported for easy comparison) are no more visible. The far-field radiation pattern shown in the figure refers to the cumulative radiation pattern obtained by integrating over the emission wavelength range of 550–600 nm and it predicts a divergence of the overall beam of  $\approx 5^\circ$  in air.

In order to observe the angular distribution of fluorescence, the leakage radiation microscope described in the first chapter is used (Fig. 1.6). The diffractive structure considered is the one schematically shown in Fig. 2.6a.



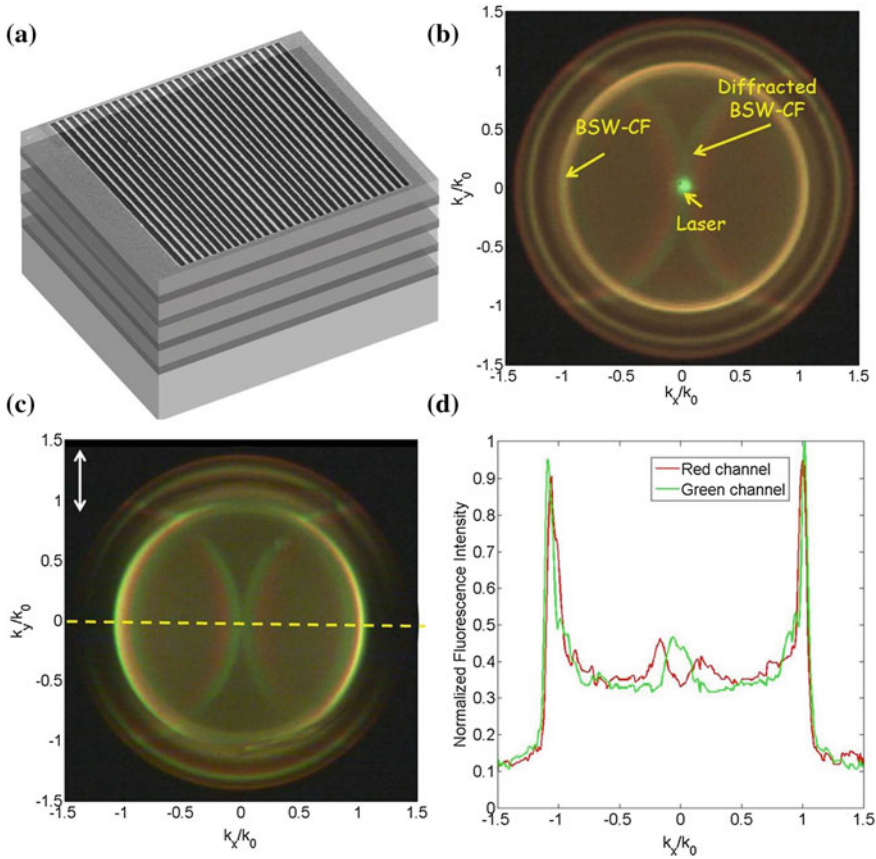
**Fig. 2.5** Cross sectional sketch of flat (a) and patterned (c) multilayer; calculated near-field intensity distribution of light radiated by an emitter close to the surface of a flat (b) and patterned (d) multilayer ( $N=10$ ); e expanded view of the intensity distribution of BSW-coupled diffracted fluorescence; f angular pattern of emitted light in the case of flat and corrugated 1DPCs, highlighting the BSWassisted beaming effect. Adapted from [22]

Figure 2.6b shows the fluorescence image of the BFP collected on the  $N = 4$  pairs design. In addition to the bright circle corresponding to the leakage of BSW-coupled fluorescence naturally occurring on the flat multilayer, the BFP fluorescence image reveals two bright arcs superposing in the center. The two additional arcs correspond to the diffracted BSW-CE, and the superposition in the center of the first diffracted orders confirms that the grating momentum matches the BSW wavevector. In this case, because of the particular orientation of the linear grating, diffraction only affects the  $k_x$  direction of propagation, through the corresponding wavevector components:

$$k_x = (2\pi/\lambda)n_{sub}\sin(\theta_x) \quad (2.2)$$

for each wavelength  $\lambda$ .

The sample with lower number of layers is considered here in order to put in evidence the correspondence of the BSW-CE and the diffracted light. It has to be



**Fig. 2.6** **a** Schematic view of the linear grating patterned on top of the 1DPC. The *top layer* is a SEM image. Adapted from [23] **b** Fluorescence BFP image obtained by collecting fluorescence coming from the patterned area. The two diffracted branches superimposing in the center confirm the BSW-coupled fluorescence diffraction. The *bright green spot* in the center is the residual laser radiation. **c** Same of (b) collected with a polarization filter (oriented according to the *white arrow*) along the collection path that puts in evidence the TE polarization of both the BSW-coupled fluorescence and the diffracted BSW-CE. **d** Intensity profile extracted along the *red dashed line* in (b), that evidences the normal beam due to the grating effect

noticed indeed that the two branches crossing in the center are the replicas of the bright ring corresponding to BSW-CE leakage radiation shifted in the  $x$  direction of an amount equal to the grating momentum.

In order to put in evidence the polarization dependence of the BSW coupling, a polarization filter has been added along the collection path (Fig. 2.6c). The image reveals the TE nature of BSWs and confirms that the diffracted light maintains the polarization state (along the white arrow), confirming that it is the BSW-CE that is diffracted.

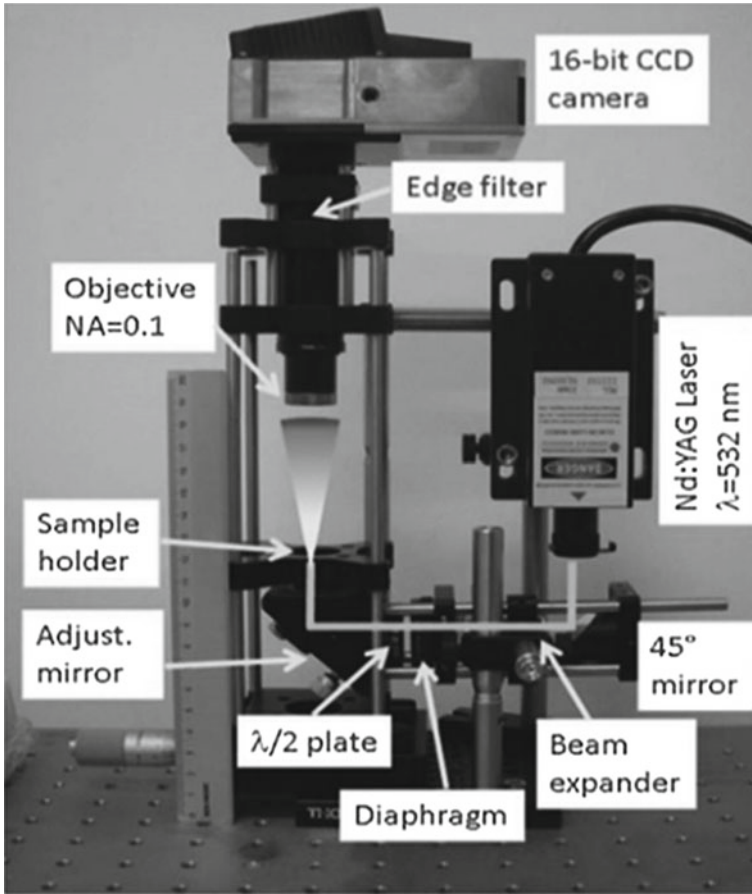
We can extract an intensity profile for both the red (R) and green (G) channels of the CMOS camera (Fig. 2.6d). The profile is taken along the  $k_y = 0$  (dashed) line in Fig. 2.6c, and the appearance of a central peak can be observed. The R channel has its maximum of sensitivity in the spectral range 580–620 nm, that is the same spectral range of the far-field pattern calculations in Fig. 2.5f. We can therefore apply the Bragg's equation for a  $\Lambda_g = 520$  nm grating. For a given wavelength  $\lambda$ , we find that  $k_x^{-1} = k_x^{BSW} - 2\pi/\Lambda_g$  results in an overall angular range  $\theta_x \approx 6^\circ$  associated with the  $-1$  diffraction order of BSW-coupled fluorescence. The chromatic dispersion of the diffracted branches reflects the dispersion of BSWs. The experimental findings well match theoretical predictions obtained with the simple two-dimensional finite element numerical model described above.

### 2.3 Enhanced Fluorescent Signal in Bio-Sensing Experiments

So far we have considered the sample with the lower number of layers in order to qualitatively show that BSW-CE can be normally diffracted by means of surface relief gratings. In the attempt to take advantage of this effect in an application, a quantification of the enhancement obtained for a given numerical aperture of the collection system is required.

To this aim, the experimental setup has been modified according to the scheme presented in Fig. 2.7. A linearly polarized 532 nm laser beam (Nd:Yag 10 mW) is expanded by means of a 0.1 NA objective and a movable lens with focal length 10 mm. The divergence of the beam can be adjusted by moving the lens. Since the grating is fabricated to normally diffract fluorescence, a small divergence of the laser beam is required in order to couple the incident radiation with the BSW and ensure a resonant excitation of fluorescence. The beam passes through an Half Wave Plate able to rotate the polarization of the incident beam and then impinges on the sample. The fluorescence excited on the surface of the 1DPC is collected by a low numerical aperture objective (Nikon 5x NA = 0.1) and spectrally filtered by an edge filter (FEL 550, Thorlabs) in order to cut off the excitation light. Fluorescence is then imaged on a CCD camera (Apogent Ascent a694) via a lens so that a real image of the sample surface is produced.

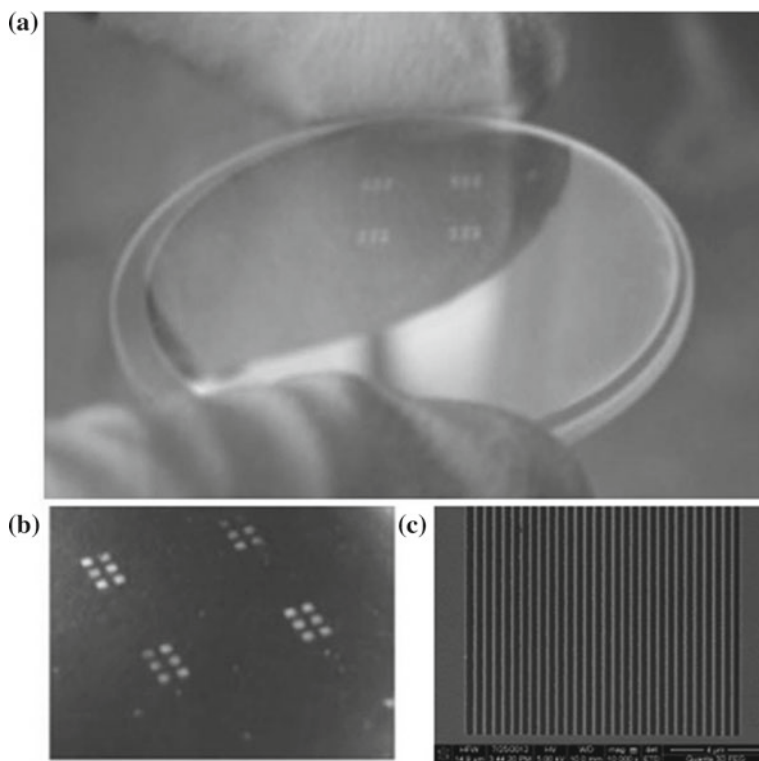
The sample is schematically depicted in Fig. 2.8a (image not in scale): a 1DPC composed by six pairs of high and low refractive index layers (same elementary cell described in the previous section) is patterned with a linear surface relief grating (period  $\Lambda_g = 495$  nm, height  $h = 80$  nm). The patterned area is composed by four groups of six squares of  $250 \mu\text{m} \times 250 \mu\text{m}$  size. The gratings are clearly visible by naked eyes under white light illumination (Fig. 2.8b, c). An homogeneous layer of a fluorescent probes is obtained by functionalizing the surface and binding thereon the labeled molecules. Different models have been tested on the same sample, demonstrating the versatility of the approach. More details about the biological models and



**Fig. 2.7** Picture of the fluorescence microscope used in the sensing experiments. Adapted from [20]

the related protocols for functionalize the photonic crystal surface can be found in *F. Frascella et al., Analyst 140, 5459* and *S. Ricciardi et al., Sens and Act B 215, 225*. The sample itself can be eventually equipped with a microfluidic chip for on-chip functionalization [19].

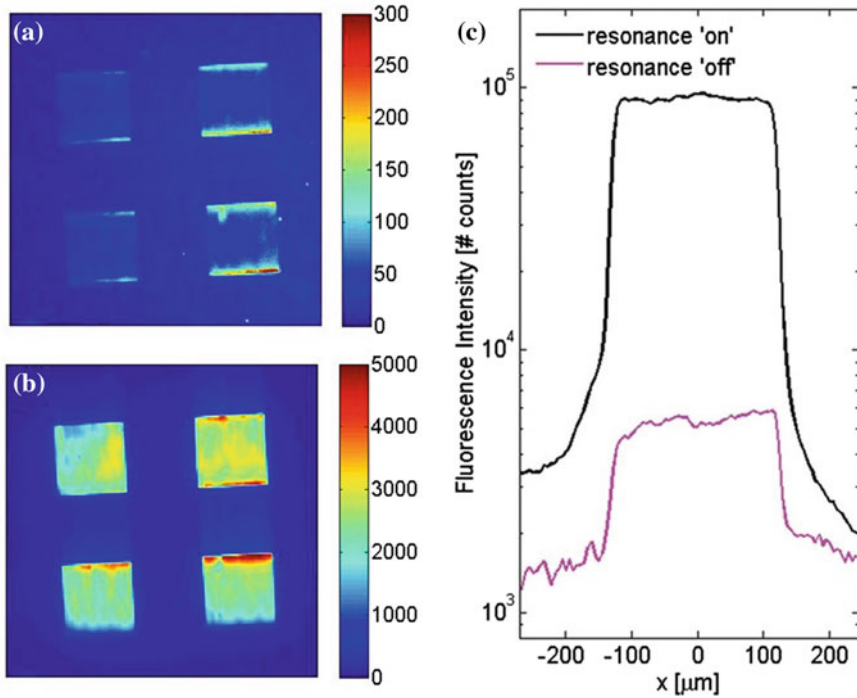
Since the signal amplification is not related to the specific molecule, we can choose a generic model to quantify the enhancement factor. To this aim we consider the c-DNA mi-RNA-16 (labeled) recognition reported in [20]. We chose a specific mi-RNA concentration (50 nM) well below the saturation level. The resonant coupling of the laser beam with the BSW mode can be easily switched on and off by rotating the Half-Wave Plate. The coupling occurs indeed only when the laser polarization is perpendicular to the grating momentum. Figure 2.9a, b correspond to the fluorescent images obtained without resonant excitation and with resonant excita-



**Fig. 2.8** Schematic view of the patterned 1DPC. **b** Picture of the four groups of linear gratings under white light illumination. **c** Image of the photonic crystal sample employed in the sensing experiments. Adapted from [20]

tion respectively. Since the fluorescent probes are homogeneously distributed on the sample surface and the laser spot is much larger than a single grating pad, the signal coming from outside the patterned areas can be taken as internal reference. By taking the intensity profiles along the two yellow dashed lines in Fig. 2.9a, b, we can compare the two signals (Fig. 2.9c). The purple line corresponds to the fluorescence intensity in off-resonance condition. In this case the enhancement factor observed is about 3 and it is only due to the angular redistribution of light. The black line corresponds to the case of resonant excitation and an enhancement factor of about 60 is obtained, meaning that the resonant excitation contributes to the overall enhancement with a factor of roughly 20.

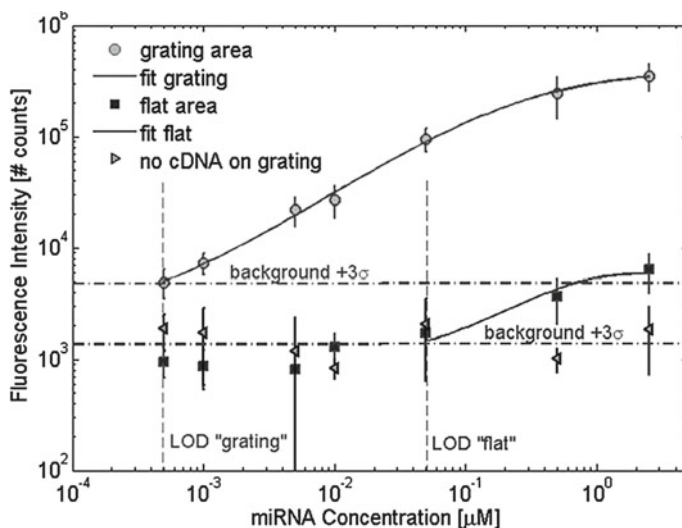
By incubating solutions at different concentrations of mi-RNA 16 it is possible to build a titration curve (Fig. 2.10). To this aim, we considered concentrations ranging from 0.5 nM to 2.5  $\mu$ M. Each concentration has been incubated on a group of six grating pads, in order to perform a statistical analysis. The error bars result from the intensity fluctuations observed on different gratings. Both the two sets of experimental data are well fitted by a sigmoidal curve, as reported in literature [21].



**Fig. 2.9** Fluorescence image (*in false colors*) of a sub-group of 4 gratings either non-resonantly (a) or resonantly (b) excited by the incident laser beam (incidence is  $1.6^\circ$ ) upon polarization rotation; c comparison of intensity profiles across one grating (yellow dashed line in (a, b)) under on-resonance and off-resonance conditions. Adapted from [20]

The two background levels have been obtained by measuring the fluorescence intensity before mi-RNA 16 incubation both inside the patterned area and on the surrounding flat surface. The two distinct level of background are due to the enhancement affecting also the autofluorescence of c-DNA and silica. The minimum detectable signal is set as  $3\sigma$ , where  $\sigma$  is obtained by computing the root mean square of the background intensity. The two curves demonstrate that the minimum concentration detectable on the flat surface is about 50 nM, whilst on the patterned area a concentration as low as 0.5 nM is still distinguishable from the background. As a result, the limit of detection is reduced of roughly 50 in concentration, and a mean enhancement factor of 60 is maintained over the entire range of concentrations.

The approach has been successfully tested also with an antigen-antibody model [22], demonstrating the versatility of the approach combined with the simplicity of the detection scheme, that can be easily implemented in a commercial wide field fluorescence microscope.



**Fig. 2.10** Fluorescence titration curves collected for different miRNA-16 concentrations, inside and outside the gratings. The reported concentration refers to the miRNA-16 molarity in the incubating solution. Adapted from [20]

## References

1. E. M. Purcell, Phys. Rev. 69, 681, (1946).
2. R. S. Meltzer, S. P. Feofilov, B. Tissue and H. B. Yuan, *Dependence of fluorescence lifetimes of  $Y_2O_3 : Eu^{3+}$  nanoparticles on the surrounding medium*, Phys. Rev. B 60, R14012(R), (1999).
3. M. Megens, J. E. G. J. Wijnhoven, A. Lagendijk and W. L. Vos, *Fluorescence lifetimes and linewidths of dye in photonic crystals* Phys. Rev. A 59, 4727, (1999).
4. N. Ganesh, W. Zhang, P. C. Mathias, E. Chow, J. A. N. T. Soares, V. Malyarchuk, A. D. Smith and B. T. Cunningham, *Enhanced fluorescence emission from quantum dots on a photonic crystal surface*, Nat. Nanotech, 2, 515–520, (2007).
5. P. Lohdal, A. F. van Driel, I. S. Nikolaev, A. Irman, K. Overgaag, D. Vanmaekelbergh and W. L. Vos, *Controlling the dynamics of spontaneous emission from quantum dots by photonic crystals*, Nature 430, 654–657, (2004).
6. I. D. Block, L. L. Chan, B. T. Cunningham, *Photonic crystal optical biosensor incorporating structured low-index porous dielectric*, Sens. and Act. B 120, 187–193, (2006).
7. W.-H. Chang, W.-Y. Chen, H.-S. Chang, T.-P. Hsieh, J.-I. Chyi and T. Hsu, *Efficient Single-Photon Sources Based on Low-Density Quantum Dots in Photonic-Crystal Nanocavities*, Phys. Rev. Lett. 96, 117401, (2006).
8. J. R. Lakowicz, *Radiative decay engineering 3. Surface plasmon-coupled directional emission*, An. Biochem. 324 (2), 153–169, (2004).
9. R. Badugu, K. Nowaczyk, E. Descrovi, J. R. Lakowicz, *Radiative decay engineering 6: Fluorescence on one-dimensional photonic crystals*, An. Biochem. 442 (1), 83–96, (2013).
10. M. Ballarini, F. Frascella, N. De Leo, S. Ricciardi, P. Rivolo, P. Mandracci, E. Enrico, F. Giorgis, F. Michelotti, and E. Descrovi, *A polymer-based functional pattern on one-dimensional photonic crystals for photon sorting of fluorescence radiation* Opt. Express 20, 6703 (2012).
11. Taflov A. and Hagness S. C. *Computational Electrodynamics: The Finite Difference Time Domain Method* 3rd edn (Boston MA: Artech House) p. 329, (2005).

12. C. J. Regan, O. Thiabgoh, L. Grave de Peralta, and A.A. Bernussi, *Probing photonic Bloch wavefunctions with plasmon-coupled leakage radiation*, Opt. Expr. 20 (8), 8658–8666, (2012).
13. S.P. Frisbie, C.J. Regan, A. Krishnan, C. Chesnutt, J. Ajimo, A.A. Bernussi and L. Grave de Peralta, *Characterization of polarization states of surface plasmon polariton modes by Fourier-plane leakage microscopy*, Opt. Comm. 283 (24), 5255–5260, (2010).
14. R. Esteban, T. V. Teperik, and J. J. Greffet, *Optical Patch Antennas for Single Photon Emission Using Surface Plasmon Resonances*, Phys. Rev. Lett. 104, 026802, (2010).
15. Y. C. Jun, K. C.Y. Huang and M. L. Brongersma *Plasmonic beaming and active control over fluorescent emission*, Nat. Comm. 2, 283, (2011).
16. H. Li, S. Xu, Y. Gu, H. Wang, R. Ma, J. R. Lombardi and W. Xu, *Active Plasmonic Nanoantennas for Controlling Fluorescence Beams*, J. Phys. Chem. C 117, 19154–19159, (2013).
17. H. Raether, *Surface Plasmons*, Springer-Verlag, Berlin (1988).
18. E. Descrovi, D. Morrone, A. Angelini, F. Frascella, S. Ricciardi, P. Rivolo, N. De Leo, L. Boarino, P. Munzert, F. Michelotti and F. Giorgis, *Fluorescence imaging assisted by surface modes on dielectric multilayers*, Eur. Phys. Journ., 68, 1–4 (2014).
19. A. Lamberti, A. Angelini, S. Ricciardi and F. Frascella, *A flow-through holed PDMS membrane as a reusable microarray spotter for biomedical assays*, Lab on Chip 15, 67–71, (2015).
20. F. Frascella, S. Ricciardi, L. Pasquardini, C. Potrich, A. Angelini, A. Chiado', C. Pederzoli, N. De Leo, P. Rivolo and E. Descrovi, *Enhanced fluorescence detection of miRNA-16 on a photonic crystal*, Analyst 140, 5459, (2015).
21. B. T. Cunningham and R. C. Zangar, *Photonic crystal enhanced fluorescence for early breast cancer biomarker detection* J. Biophotonics 5, 617 (2012).
22. S. Ricciardi, F. Frascella, A. Angelini, A. Lamberti, P. Munzert, L. Boarino, R. Rizzo, A. Tommasi and E. Descrovi, *Optofluidic chip for surface wave-based fluorescence sensing*, Sens. and Act. B 215, 225–230, (2015).
23. A. Angelini, E. Enrico, N. De Leo, P. Munzert, L. Boarino, F. Michelotti, F. Giorgis and E. Descrovi, *Fluorescence diraction assisted by Bloch surface waves on a one-dimensional photonic crystal*, New J. Phys. 15, 073002, (2013).

Photon Management Assisted by Surface Waves on  
Photonic Crystals

Angelini, A.

2017, XX, 64 p. 43 illus., 37 illus. in color., Hardcover

ISBN: 978-3-319-50133-8