Propagation and localization of quantum dot emission along a gap-plasmonic transmission line

M. Castro-Lopez, A. Manjavacas, J. García de Abajo, and N. F. van Hulst

1 ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science & Technology, Castelldefels (Barcelona), Spain
2 Current address: Department of Physics, King’s College London, Strand, London, UK
3 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA
4 ICREA - Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain
5 Marta.Castro-Lopez@KCL.ac.uk
6 Niek.vanHulst@ICFO.eu

Abstract: Plasmonic transmission lines have great potential to serve as direct interconnects between nanoscale light spots. The guiding of gap plasmons in the slot between adjacent nanowire pairs provides improved propagation of surface plasmon polaritons while keeping strong light confinement. Yet propagation is fundamentally limited by losses in the metal. Here we show a workaround operation of the gap-plasmon transmission line, exploiting both gap and external modes present in the structure. Interference between these modes allows us to take advantage of the larger propagation distance of the external mode while preserving the high confinement of the gap mode, resulting in nanoscale confinement of the optical field over a longer distance. The performance of the gap-plasmon transmission line is probed experimentally by recording the propagation of quantum dots luminescence over distances of more than 4 \( \mu \text{m} \). We observe a 35% increase in the effective propagation length of this multimode system compared to the theoretical limit for a pure gap mode. The applicability of this simple method to nanofabricated structures is theoretically confirmed and offers a realistic way to combine longer propagation distances with lateral plasmon confinement for far field nanoscale interconnects.

© 2015 Optical Society of America

OCIS codes: (350.4238) Nanophotonics and photonic crystals; (250.5403) Plasmonics; (230.7370 ) Waveguides.

References and links
1. H. Raether, Surface Plasmons on Smooth and Rough Surfaces and on Gratings (Springer, 1988).
1. Introduction

The negative permittivity of metals below the plasmon frequency allows us to challenge the diffraction limit of light by means of the surface plasmon polaritons (SPPs) occurring at the interface between the metal and a dielectric [1]. Since the optical field of a SPP is bound to the metal, it is confined to the surface on the nanometer scale [2]. This strong localization has pushed the development of ‘plasmonics’ towards a promising combination of the speed and bandwidth of light together with sizes characteristic of electronic circuits [3, 4]. However, metals exhibit high intrinsic losses at optical frequencies, [5] which have stimulated the development of alternative designs, such as plasmonic transmission lines (PTLs), in order to increase the relatively short propagation distance of SPPs [6] while maintaining the nanoscale light confinement [7–9].

Numerous experimental and theoretical studies have explored different PTL designs, including nanogrooves [10–13], sharp wedges [14–16], thin metal films [17–20], dielectric nanoholes [21, 22], slot waveguides [23–27], chains of metallic particles [28–30], metal nanotrips on dielectric media [31–33], dielectric nanowires on metallic surfaces [34, 35], metallic...
nanorods, [21,36–39] and double-wire (DW) transmission lines [40,41]. Most of these types of systems have been shown to be theoretically and/or experimentally very promising at infrared wavelengths. However their performance decreases very rapidly when approaching the visible regime.

A particularly interesting structure is the double wire (DW) transmission line (the so called gap-plasmon waveguide). Since the gap plasmon mode that propagates along the gap of this DW travels confined within the dielectric separation between two metallic wires, it experiences less the presence of the metal compared to other types of PTLs that present similar strong mode confinement. This decreases the losses and therefore increases the propagation distance while maintaining a very strong confinement inside the gap [40]. In addition, the presence of two gap antennas at the beginning (receiving antenna) and at the end (emitting antenna) of the DW has been theoretically shown to improve the overall performance of the system as an optical interconnect (i.e., receiving, propagating, and delivering energy from one end to the other) [41, 42]. For example, the receiving antenna can increase by two orders of magnitude the coupling efficiency from the far-field to the waveguide. Likewise, the emitting antenna can increase the power transmission through the system (from one antenna to the other) by means of impedance matching (i.e., by reducing the reflectivity at the end facets of the wires).

To explore the limits of the propagation length of the DW transmission line (TL), here we present an alternative mode of operation which relies on the multimode character of this type of waveguide [43, 44]. It consists of the propagation of plasmons via the interference of two modes [45,46], namely, (1) the gap plasmon mode (first order symmetric mode, i.e., the bonding combination of the monopolar modes of the nanowires) and (2) the external plasmon mode (second order symmetric mode, i.e., the bonding combination of the dipolar modes) [43]. This way of operation takes advantage of both the long propagation distance of the outer plasmon mode and the strong confinement of the gap plasmon mode. By tailoring the length of the DW PTL, we theoretically show that the propagated intensity can still be highly confined at the gap of the emitting antenna, while the plasmon can propagate further than the gap plasmon mode alone. We experimentally confirm the viability of this method, by coupling the luminescence of QDs to this kind of structure [39,47] and showing propagation distances of more than 4 µm, while measuring an intrinsic propagation length longer than the one theoretically predicted for the pure gap plasmon mode. The performance of the DW system is experimentally and theoretically compared to the most simple case of PTL (i.e., the single-wire (SW) PTL).

2. Experimental methods

Figure 1 shows an overview of the experiment. The structures under study were fabricated by e-beam lithography following standard procedures (see ‘Fabrication’ in the Appendix). The cross section of each wire is the same for the three PTLs (110 nm in width and 40 nm in height) and the gap of the DW and DWA systems is 45 nm. The dimension of the antennas at the end of the DWA is 440×50×40 nm (length, width, and height respectively). The PTLs are covered with a thin film (~20 nm thickness) of highly packed QDs (Invitrogen organic QDs, λ_{em} = 770 nm, FWHM = 90 nm) and a cover layer (~300 nm thickness) of PMMA to guarantee the uniformity of the refractive index (Fig. 1(a)). The SEM images of the fabricated SW, DW, and DWA structures are shown in Figs. 1(b)–1(d) respectively. The propagation is measured by normal confocal microscopy using a fix excitation laser spot (λ_{exc} = 640 nm, repetition rate 25 MHz, pulse width τ = 50 ps, focal spot ~ 1 µm) linearly polarized perpendicular to the wires and focused from the top of the sample through an air objective (Olympus, MPlanApoN 50x/0.95). The excitation spot is placed at the center of each structure while the detection is scanned from the bottom using an oil immersion objective (Zeiss, Plan-Apo 100x/1.46) and can be spatially and spectrally resolved for each polarization component. Using this method,
Fig. 1. Schematic of the experiment. (a) The gold structures under study are lithographed on top of a thin film of ITO and covered with a thin layer of QDs protected with a layer of PMMA. The propagation of QD luminescence is studied for the three plasmonic transmission lines shown in the SEM images: (b) single-wire (SW), (c) double-wire (DW) and (c) double-wire loaded with two gap antennas (DWA). (e) Confocal image of a DWA covered with QDs. The QDs are excited from the top at a fix position (central bright spot), their luminescence is coupled to the structure, and the propagation is detected from the bottom by a scanning objective. Propagation of the luminescence beyond 4 µm is observed at the out-coupling antennas.

we observe QD luminescence propagation through DWA structures coupled out at the antennas at distances of 4.4 µm (Fig. 1(e)) while no luminescence is detected at the end of SW systems.

3. Theoretical methods
To understand the differences in performance between the three structures under study, we theoretically compare the intrinsic parameters characterizing the modes present on each PTL.
Using boundary-element method (BEM) [48, 49] calculations of infinite SW and DW systems (see ‘BEM calculations’ in the Appendix), with similar cross section and environment as the fabricated ones, we determine the local density of optical states (LDOS, i.e., the combined strength of all photon modes as a function of frequency and position, see [50] for a discussion of this quantity) for each structure at the wavelengths of interest (i.e., laser excitation at 640 nm and QD maximum of luminescence at 770 nm). The LDOS obtained using BEM allows us to get at once all the intrinsic parameters describing the modes present in the structure for any wavelength of interest. Being proportional to the decay rate of an emitter placed at that point, the LDOS normalized to its value in vacuum (Fig. 2) gives a direct measure of the performance of the waveguide in these kinds of hybrid systems. Figures 2(a) and 2(b) shows the LDOS of the SW and DW structures at 640 nm (dashed line) and 770 nm (solid line), respectively, as a function of parallel wave-vector (k||). Two modes are present for each pair wavelength/PTL-type (marked in the graphs). The LDOS spatial distribution for the four modes of interest at the wavelength of the QDs emission shows the energy localization around the wires (insets).

From the results shown in Fig. 2 we extract intrinsic parameters (the propagation length (L) and the mode size (Λ)) for each mode. First of all, the propagation length can be calculated as [40]

\[ L = \frac{1}{2 \times \text{Im}(k||)} = \frac{1}{\text{FWHM}_{\text{LDOS}}} \]  \hspace{1cm} (1)

Additionally, the mode size, defined as the inverse of the distance between wave-vector (k||) and light-line (k0) [33], can be calculated as \( \Lambda = (k|| - k0)^{-1} \). We define the figure of merit of the system as the ratio between propagation and spatial confinement: \( F = L / \Lambda \) [51]. Table 1 summarizes the guiding properties of the modes under study, showing their wave-vectors and correspondent propagation length L, mode size Λ, and figure of merit F.

| PTL  | Mode  | \( \lambda_{\text{exc}} \) (nm) | k|| (nm\(^{-1}\)) | L (nm)   | Λ (nm) | F   |
|------|-------|-------------------------------|-----------------|----------|--------|-----|
| SW   | first | 640                           | 0.0242184       | 414.9    | 69.4   | 6   |
|      |       | 770                           | 0.0171400       | 1317.5   | 111.4  | 12  |
|      | second| 640                           | 0.0163627       | 675.7    | 152.8  | 4   |
|      |       | 770                           | 0.0116800       | 16317.5  | 284.1  | 57  |
| DW   | gap   | 640                           | 0.0277255       | 369.0    | 55.8   | 7   |
|      |       | 770                           | 0.0200100       | 1124.5   | 84.4   | 13  |
|      | external | 640                          | 0.0192385       | 460.8    | 106.1  | 4   |
|      |       | 770                           | 0.0126100       | 3377.4   | 224.7  | 15  |

These values clearly show that a wavelength of 640 nm propagates poorly compared to 770 nm in both SW and DW PTLs. The main reason for that is the stronger metallic losses taking place at shorter wavelengths. The second mode of the SW at a wavelength of 770 nm shows the largest propagation length and figure of merit. However, its large mode profile increases the cross-talking with neighboring waveguides limiting their integration in nanophotonic devices. The larger mode profile of the SW also limits its coupling efficiency to single emitters and nanosources restricting its applicability to these kinds of hybrid systems. In this respect, it
is important to note that the gap mode presents higher confinement. However, its short propagation length limits considerably its figure of merit. In contrast, for the external mode, while its propagation length is three times longer, the mode size is very large, limiting again its figure of merit. Nevertheless, the existence of these two modes opens the possibility of making them interfere and take advantage of both the high confinement of the gap mode and the long propagation of the external mode.

When studying the propagation of the fluorescence originating in randomly positioned QDs,
Fig. 3. Simulated transmission differences between the SW, DW, and DWA systems. (a) Simulated spectral transmission of the three PTLs normalized in the same way, and obtained upon local excitation by a dipole ($\lambda_{\text{dip}} = 770$ nm). The transmission of the DW (black line) and the DWA (black line with crosses) is practically the same, while the transmission of the SW (red line, $\times 5$) is considerably lower. The emission of the QDs (FWHM marked in gray) matches better the DW/DWA systems. When the polarization of the dipole is parallel to the PTLs, the transmission decreases one order of magnitude for the SW (red dashed line) and two orders of magnitude for the DW/DWA (black dashed line). (b) Simulated (black line) and fitted (red line with crosses) intensity decay profiles for the SW, DW, and DWA systems (top, middle, and bottom, respectively) being locally excited by a dipole located at 4$\mu$m from the end of the wires (inset). The simulated intensity decay and the fitted curve used to calculate $Z_L$ match almost perfectly.

we need to consider the coupling to both the gap and external modes. The propagated intensity will therefore be determined by the superposition of these two modes. Each of them can be
described mathematically as \( A_i = A_{0i} e^{-\gamma_i x} e^{j\beta_i} \); where \( A_{0i} \), \( \gamma_i \), and \( \beta_i \) are the amplitude, propagation constant, and phase of the \( i \) mode (\( i \in (1, 2) \)) respectively. The propagation constant is defined as \( \gamma_i = \alpha_i + j\beta_i \), where \( \alpha_i \) is the attenuation constant (i.e., the inverse of twice the propagation length or \( (2L)^{-1} \)) and \( \beta_i \) is the phase constant (i.e. the real part of the wave-vector or \( k_i \)). Therefore, the addition of both modes will result (after several trigonometric equivalences and regrouping of constants) in an effective interference

\[
A_{int} = A_1 + A_2 = e^{-\gamma \cdot x}[A_{02} e^{j\beta_1} e^{\gamma \cdot x} + A_{01} e^{j\beta_2} e^{-\gamma \cdot x}]
\]  

(2)

where \( \gamma \) and \( \gamma_m \) are

\[
\gamma = \alpha_c + j\beta_c = \frac{\alpha_1 + \alpha_2}{2} + j\left(\frac{\beta_1 + \beta_2}{2}\right)
\]

(3)

\[
\gamma_m = \alpha_m + j\beta_m = \frac{\alpha_1 - \alpha_2}{2} + j\left(\frac{\beta_1 - \beta_2}{2}\right)
\]

(4)

Equation (2) can be seen as the product of two waves with propagation constants \( \gamma \) and \( \gamma_m \). Both \( \gamma \) and \( \gamma_m \) are determined by the attenuation and phase constants, \( \alpha \) and \( \beta \), of the two interfering modes as shown in Eqs. (3) and (4). Since the values of \( \beta_1 \) and \( \beta_2 \) are close to each other, \( \beta_m \) is much smaller than \( \beta_c \). Therefore, it is possible to see the effective interfering mode as a carrier wave (resulting from the interference mentioned above) propagating with \( \gamma_c \), for which the amplitude is being spatially modulated by another wave with \( \gamma_m \). This modulation determines how the amplitude of the interference is evolving in space, and therefore, it also determines the effective value of the propagation length of each wave \( (L_{int}) \) at each position. From Eq. (2) we see that the strength of the modulation, hence the value of \( L_{int} \), depends on the relative amplitudes of the two modes \( (A_{01}, A_{02}) \). While the maximum \( L_{int} \) is limited by the largest propagation length of the interfering modes (i.e., \( L_{int} \leq \max\{L_i\} = 3377.4 \text{ nm in this case} \)), it appears to be sufficient to have an amplitude of the external mode half that of the gap mode to increase the propagation length of the interference above that of the gap mode alone (see ‘Interference between modes’ in the Appendix). In the experiments presented here, the excitation of the randomly distributed QDs is done by a Gaussian beam with a FWHM of 1\( \mu \)m centered at the gap of the DWA. The QDs act as localized sources, so we assume an even excitation of both modes, which sets the effective propagation length of the interference \( (A_{01} = A_{02} \text{ in Eq. (2)}) \) as approximately the average of both modes, i.e., \( L_{int} \approx (L_1 + L_2)/2 \). For the DWA under study being excited at 770 nm wavelength, the effective propagation length of the interference is \( L_{int} \approx 2251 \text{ nm (i.e., twice that of the gap mode)} \).

Because the amplitude of the propagated wave is modulated, this type of interference results in the appearance of spatial beats [45,46] (similar to the acoustic beats generated by two interfering tones of slightly different frequencies). The location and periodicity of the nodes of these beats are determined respectively by the relative phase between the modes and the difference between wave-vectors \( \beta_1 - \beta_2 \). As both modes interfere constructively/destructively at specific positions, the intensity inside the gap is maximum at periodic distances. By locating the end of the DW at one of these positions where the energy is highly confined at the gap, the mode size \( (\Lambda_{int}) \) would stay very small. In combination with the larger \( L_{int} \), this could increase the effective figure of merit of the DWA system from \( F = 13 \) or 15 (for the gap mode or external mode, respectively) to the theoretical limit of \( F_{eff} = L_{external}/\Lambda_{gap} = 3377.4/84.4 = 40 \). Note that since \( F_{eff} \) is an effective figure of merit which depends on the position, this theoretical limit is only achievable at specific locations. The advantage of locating the out-coupling antennas at any of these positions is shown at the end of this section and Fig. 4. Also note that similar reasoning will hold for each set wavelength/PTL-type.

In order to get a quantitative comparison between the three types of structures, we performed FDTD simulations (see ‘FDTD simulations’ in the Appendix) and obtained the transmission

---

© 2015 OSA

16 Nov 2015 | Vol. 23, No. 23 | DOI:10.1364/OE.23.029296 | OPTICS EXPRESS 29304

#247219

Received 6 Aug 2015; revised 14 Oct 2015; accepted 27 Oct 2015; published 2 Nov 2015
Fig. 4. Simulated spatial intensity distribution of the interference in a DWA with length \( \approx 6 \mu \text{m} \). The source is located at the gap and displaced to the left around 160 nm from the center position. (a) The intensity of the interference bounces from the gap towards the outside of the wires with a beat period of \( \beta_2 - \beta_1 \). (b) The left antenna is located at a position where the maximum of the interference is in the gap, thus strongly localized. (c) The right antenna is located at a position where the maximum is outside the wires, thus the intensity at the gap of the antenna is minimum. The effective figure of merit \( F_{\text{eff}} \) at the position of the left antenna is higher than at the right antenna.

efficiency of the structures in the spectral region of interest (Fig. 3(a)). While the transmission of the SW (red curve, \( \times 5 \)) is very low in the QD luminescence region (gray area), the transmissions of the DW (black curve) and DWA (black curve with crosses) are exactly the same and match the QD emission region. Additionally, when the polarization of the excitation is parallel to the wires, the transmission decreases by 2-3 orders of magnitude for the three systems (dashed curves) since both, gap and external modes, involve electric fields mainly perpendicular to the PTL. The equivalence between DW and DWA transmission efficiencies indicates that the antennas at the end of the DWA structure are not influencing the propagation through the
structure (see ‘Power radiated by the source’ in the Appendix). However, the emission of the QDs is matching the 4th order resonance mode of an antenna of these dimensions (see ‘Antenna resonance’ in the Appendix) which increases the power radiation in the DWA compared to the DW. Besides, to determine the relative impedance match between PTL and its relative load, we first calculate the intrinsic impedance ($Z_0$) of each PTL [44] (see ‘Intrinsic impedance of the DW’ in the Appendix). The impedance of the load ($Z_L$) is related to the strength of the mode reflection ($\Gamma$) as [52, 53]:

$$Z_L = Z_0 \frac{1 + \Gamma}{1 - \Gamma} \quad (5)$$

We obtain $\Gamma$ and $Z_L$ for each PTL by fitting the FDTD intensity decay profile using Eq. (2) (Fig. 3(b)). Due to the large number of fitting variables, in order to reduce the error and help the convergence of the fit, we feed as starting values the mode parameters obtained with the BEM calculations (Table 1). By doing so, we determine the strength of the mode reflection at the end facets of the SW (top), DW (middle), and DWA (bottom). We obtain a partial impedance matching between $Z_L$ and $Z_0$ for the DWA that reduces in 20% the mode reflection and thus increases the power delivery to the load compared to the DW and the SW (see ‘Intrinsic impedance of the load’ in the Appendix). Moreover, since the load in the DWA system is an antenna resonant with the QD emission, this power is efficiently radiated to the far field, increasing even further the experimental performance of the DWA.

Finally, as commented above, we take advantage of the intensity beatings of the interference to confine the intensity to the gap of the antenna. This is illustrated in Fig. 4, where the intensity emitted from a dipole - located at the gap of a DWA structure, but shifted 160 nm towards one of the antennas - is confined at different areas when reaching the left/right end of the DWA. While the propagation length is approximately the same for both situations, the mode confinement at the end of the left side of the DWA (Fig. 4(b)) is higher than at the right side (Fig. 4(c)) which leads to an increase of its $F_{\text{eff}}$. The stronger confinement inside the gap of the left antenna leads to an increase in the out-coupling efficiency, and therefore, also an effective increase in the power radiated towards the far field.

4. Results and discussion

The good performance of the DWA is experimentally corroborated by measuring the propagation of the QD luminescence through it and comparing it to the SW. Indeed, while the confocal image of the SW (Fig. 5(a)) does not show any light at the end of the wire, the measurement of the DWA system (Fig. 5(b)) shows two clear light spots at both ends. Note that these light spots cannot be attributed to antenna scattering from direct QDs luminescence since they are not visible when the laser is off the gap position. Figure 5(c) plots in logarithmic scale the intensity profile integrated across the dashed boxes marked in the confocal images. In order to confirm the nature of the light coming out at the end of the DWA, we measure the spectrum of the emission at both positions (i.e., center and end, of a 8 \( \mu \)m long structure). As shown in Fig. 6(a) both spectra present a relative shift [47]. Using the transmission efficiency obtained from FDTD simulations (replotted in Fig. 6(a) for reference) we are able to recover the original spectrum of the QDs by performing the following operations:

$$\text{losses} = \frac{T_x(500\text{nm}) - T_x(4500\text{nm})}{\text{max}(T_x(500\text{nm}))} \quad (6)$$

$$QD_{\text{comp}}(\text{end}) = \frac{QD(\text{end})}{1 - \text{losses}} \quad (7)$$

$$QD_{\text{recon}} = \frac{QD(\text{center}) + QD_{\text{comp}}(\text{end})}{\text{max}(QD(\text{center}) + QD_{\text{comp}}(\text{end}))} \quad (8)$$

© 2015 OSA
Fig. 5. Experimental comparison between DWA and SW systems. Both structures have a length of 5\(\mu\)m. (a) Confocal image of the SW system showing no emission at the ends of the guide. (b) Confocal image of the DWA system showing light emission at the ends of the guide, where the antennas are located. The light spots of the DWA allow us to estimate the propagation length of the system. (c) Experimental intensity profile in logarithmic scale along the DWA (black line) and the SW (red line) obtained by integrating the intensity across the transversal direction between the dotted lines of (a) and (b).

Where \(T_x(500\text{nm})\) and \(T_x(4500\text{nm})\) correspond respectively to the spectral transmission intensity simulated at a position 500 nm and 4500 nm away from the source; \(QD(\text{end})\) and
Fig. 6. Analysis of the spectrally resolved plasmon propagation. (a) Spectrum measured at the position where the QDs are directly excited by the laser (black curve) and at the end (red curve) of the DWA. The simulated spectral transmission of the DWA (gray dotted curve) is plotted for reference. (b) Spectrum measured outside the DWA (blue curve) and spectrum reconstructed (black curve) from the spectra in (a). The good agreement between these spectra indicates that the light being propagated through the DWA is the luminescence of the QDs and not the laser excitation.

$QD_{\text{(center)}}$ correspond to the intensity measured at the end and at the center of the DWA; $QD_{\text{comp}}(\text{end})$ corresponds to the $QD(\text{end})$ intensity after being compensated for the propagation losses; and $QD_{\text{recon}}$ corresponds to the final reconstructed intensity of the QDs. Figure 6(b) shows the perfect match between this reconstructed spectrum (black line) and the original QDs spectrum measured outside the DWA (blue line). This is a strong indication of the fact that the luminescence of the QDs is being propagated through the two wires and decoupled out at the end of it by the two antennas (further analysis of this light propagation can be found in ‘Luminescence propagation’ in the Appendix).

The fraction of light coupled out by the antennas and collected by the objective is sufficient to estimate the propagation length of the DWA. This is done by moving the excitation spot along the PTL and placing it at different distances from the ends of the TL. At each of these positions, the intensity coming out from the ends of the wires can be measured. As shown in Fig. 7, this intensity can be plotted as a function of the distance between the excitation spot and...
the out-coupling position.

Each of the points in Fig. 7 corresponds to a measurement of the relative intensity between the center of the excitation spot and one of the antennas (i.e., each of the confocal images gives two points on the graph). Since this intensity is related to the actual distance between both light spots, Fig. 7 is a direct plot of the intensity decay due to propagation [54, 55]. In order to exclude the luminescence coming from directly excited QDs, only relative distances larger than 500 nm have been considered. The field amplitude of the resulting interference wave that is being propagated through the structure can be written as $A = A_0 e^{-x/L_{\text{eff}}} e^{i\theta}$, where $A_0$ is the amplitude and $L_{\text{eff}}$ is the propagation length ($\theta$ is the phase). The fitted propagation length using the logarithmic of this function (Fig. 7 red line) is $L_{\text{eff}} = 1.5 \mu m \pm 0.1 \mu m$ ($\chi^2 = 0.07$, $R^2 = 0.8$), which is 400 nm larger than the theoretical value of $L$ for the gap mode. As mentioned above, the relative intensity of the gap and external modes determines the propagation length of the interference wave. Since the excitation sources (QDs) are distributed randomly over the structure, the relative intensity of these initial modes varies from measurement to measurement, essentially increasing the error of the fit. Similarly, each of the QDs excited inside the 1 $\mu m$ focal spot generates a slightly different beat pattern (i.e., shifted in position and with different beat period depending on the relative coupling to the initial modes), which is integrated in the same single measurement hiding any finer details of the spatial dependence signature in our data. Note that it is not possible to construct such a graph for the single-wire system since the light at the ends of the wire falls below the noise level of the confocal image. Therefore, the propagation distance cannot be resolved. This further confirms the importance of the antennas.

![Fig. 7. Propagation distance of the DWA. Relative intensity between the light spot at the center and at the end of the guide plotted against their relative distance. The data are extracted from multiple confocal images of DWA systems with different lengths (between 4 and 8 $\mu m$) but similar dimensions. Each of the confocal images gives two points in the graph (i.e., for the two DWA ends). Linear fit of the data points to an exponential decay produces a propagation length of 1.5 $\mu m \pm 100$ nm for the DWA.](image)
not only to decrease the reflection at the end of the PTL but also to efficiently couple out the light from the PTL towards the far-field.

The obtained experimental propagation length is 35% larger than the theoretical propagation length of the gap mode alone. Although similar differences have been observed in recent works [38], the explanation in that case was related to an experimental error of the measured dimensions of the synthesized nanowires and to inaccuracies of the tabulated values for the dielectric function of the metal. Here we show that the increase in $L_{\text{eff}}$ compared to the theoretical limit predicted for the gap mode can be explained via the effective interference wave. Notice that, even with a single emitter source located at the gap of the structure, the relative intensity between gap and external modes will be 2:1 (as shown in the LDOS graph in Fig. 2(b)). It is therefore not possible to locally excite a single mode by a nanometer emitter, and consequently, the interference between modes will always determine the propagation of the intensity. This interference could work in favor of optimizing the ratio between propagation distance and mode volume, and hence improve the effective figure of merit, as experimentally shown here. Although the experimental values presented in this work are still far from the efficiency numbers necessary for real implementation on integrated circuits, the viability of this kind of PTL and the methods described here are a good asset for the design of interconnects at the few-micron scale.

5. Conclusion

In conclusion, we have presented a method based on mode interference that allows us to increase the effective figure of merit of a PTL at specific positions. For the DWA, out-coupling antennas located at any of these positions can be excited more efficiently, leading to an increase in the power radiated to the far field. We experimentally measure an effective propagation distance, from the analysis of the interference pattern, that is 35% larger than the one theoretically predicted for the gap mode alone. Although the experimental values shown here are far from the efficiency numbers necessary for real implementation on integrated circuits, further improvements of the DWA system could be achieved by simple tailoring the dimensions of its components (i.e., the length of the antenna arms for better matching of the resonance length, the size of the gap for higher confinement, or the width and length of the wires for better impedance matching). The viability of this method is clearly supported by our experiments and simulations and could open the way for single-emitter interconnects via plasmon propagation.

6. Appendix

6.1. Fabrication

The structures are fabricated on top of a 10 nm ITO thin film onto a glass substrate via electron beam lithography using PMMA as positive photoresist. After development, 40 nm of gold is thermally evaporated on top of the lithographed pattern. Dichloromethane is used as solvent for the lift-off process. The total length of the fabricated structures varies between 4 and 8 $\mu$m while the height is kept at 40 nm. The width of the two wires forming the DW PTL is 110 nm each, while the gap between them is around 45 nm. On the other hand, the SW PTL fabricated for comparison has also dimensions between 4 and 8 $\mu$m in length and 110 nm in width. The width and the length of the two gap antennas at the end of the DWA PTL are 50 nm and 440 nm, respectively.

The structures are covered with a QD solution made with organic QDs (Invitrogen, Qdot ITK) embedded in PMMA (Allresist, AR-P 950K). The maximum emission of these QDs is around 770 nm (FWHM = 90 nm) while their absorption band is very broad increasing towards shorter wavelengths. The concentration of QDs is high enough ([10:1] in volume of PMMA) to
ensure the formation of a homogeneous but highly packed thin layer on top of the whole structure. The creation of such a uniform layer of QDs is checked by normal confocal microscopy (Fig. 8 up-right). A similar area is also shown in the SEM image of Fig. 8 bottom-left (before being covered with QDs).

Finally, a thick film of PMMA ($\approx 300$ nm), which refractive index ($\epsilon_{PMMA} \approx 2.01$) is very close to glass ($\epsilon_{glass} \approx 2.22$), is spincoated on top of the QDs layer. This PMMA film protects the QDs against degradation and guarantees a nearly homogeneous environment around the PTL. A constant refractive index around the structure is necessary for the correct operation of the guiding.

6.2. BEM calculations

Boundary element method (BEM) calculations [48, 49] are done for the case of single-wire (SW) and double-wire (DW) PTLs without the gap antenna. These calculations obtain the local density of states (LDOS) which give information about all the modes present in the structures, i.e. enhancement, propagation length and mode confinement. For that purpose, these calculations only consider the case of infinite PTLs (although the aspect ratio and the gap of the structures are the same as in the experiments i.e. width 110 nm, height 40 nm and gap 45 nm). Two wavelengths are chosen for characterization of these PTLs; the emission wavelength of the QDs ($\approx 770$ nm) and the excitation wavelength of the laser ($\approx 640$ nm). This allows to compare the propagation of direct laser light coupled from the far-field with the propagation of the locally coupled luminescence of QDs. The relative permittivity of the environment for these simulations is chosen to be equal to 2 which is close enough to the dielectric constant of PMMA ($\approx 2.01$) and glass ($\approx 2.22$). The complex frequency-dependent permittivity of gold has been taken from [56]. The calculations shown in Fig. 2 of the main text have been done at a distance of 22.5 nm from the metallic wires, in both cases SW and DW, what corresponds to the center of the gap (45 nm) for the DW.

Fig. 8. DWA covered with a QD layer. SEM image (bottom-left) and confocal image (up-right) of the DWA structures. The confocal image shows the homogeneity of the QDs layer.

#247219

Received 6 Aug 2015; revised 14 Oct 2015; accepted 27 Oct 2015; published 2 Nov 2015
© 2015 OSA
6.3. Interference between modes

The propagation length of the interference is determined by the relative strength of the two initial modes as explained in the main text and shown in Fig. 9(b) for the modes of the DWA. If the amplitude of the external mode \( A_{01} \) is half the amplitude of the gap mode \( A_{02} \), the propagation length of the resulting interference is larger than that of the gap mode alone (Fig. 9(b) middle). On the other hand, when \( A_{01} \approx A_{02} \) (Fig. 9(b) top), the interference mode propagates with similar propagation constants as the external mode but with spatial beatings which can confine the energy at determined positions.

![Image](image_url)

Fig. 9. Intensity propagation decay of the two modes and the interference mode in logarithmic scale. (a) intensity propagation for the three systems SW (up), DW (middle) and DWA (bottom) for the first mode (black line), second mode (red line) and the interference between both (blue line). The beating period of the interference mode is given by the difference between the \( k_{ij} \) of each mode. (b) Intensity propagation for the DWA when the relative value of the amplitude of the external mode \( A_{01} \) black line) and the amplitude of the gap mode \( A_{02} \) (red line) is varied from \( A_{01} = A_{02} \) (top), \( A_{01} = 0.5A_{02} \) (middle) and \( A_{01} = 0.15A_{02} \) (bottom). The interference between modes (blue line) follows the propagation parameters of the stronger mode.

6.4. FDTD simulations

Finite difference time domain (FDTD) simulations are done for the case of SW and DW TLs with and without the gap antennas (DW and DWA respectively). These simulations give information about the losses, impedances and the spectral transmission differences between these three systems. The spatial intensity distribution of the interference modes is also obtained by this method. For that purpose, the dimensions of the simulated gold [56] structures are the same as the fabricated ones and they are placed on top of and ITO/glass substrate and embedded in PMMA. For these simulations a broadband dipole (from 600 to 900 nm wavelength) centered inside the gap (22.5 nm away from the wire in the case of the SW) and located 15 nm above the substrate is used to locally excite all the modes of the structures. The length of the three PTLs is chosen to be 4 \( \mu \)m towards one side of the excitation position (dipole position) and infinite towards the other side. In this way, it is possible to obtain the differences in propagation be-
tween an infinite PTL and a PTL with a finite length of 4\mu m. The polarization of this dipole is varied from perpendicular (\(y\)-oriented) to the PTLs to parallel (\(x\)-oriented) in order to obtain the polarization transmission differences. A series of plane monitors placed at different distances from the excitation position (dipole position) allow to obtain the transmission spectra and the relative losses of each structure.

6.5. Power radiated by the source

In order to further confirm that the DW and the DWA present no differences from the point of view of the source, a box monitor (20 nm in side) surrounding the dipole allows to calculate the power radiated by it. Since the monitor measures the value of the Pointing vector (\(\mathbf{P}\)) 10 nm away from the dipole in every direction, the radiated power can be calculated as

\[
\text{Power} = \frac{1}{2} \int_{\text{surface}} \text{Re}(\mathbf{P})ds
\]  

Figure 10 shows the calculated radiated power of a dipole for the DW (black line), the DWA (red line) and the SW (blue line) systems normalized by the power radiated by the same dipole in an homogenous media. The dipole is located in the middle of the gap for DW and DWA systems which corresponds to a distance of 22.5 nm from the wire in the case of the SW. The distance between the dipole and the end of the guides is 4 \mu m. It is clear that the power radiated by the dipole at systems DW and DWA is practically the same, confirming that the source does not ‘see’ the antennas (as expected for PTLs of this length). The power radiated by the dipole in the SW (blue line) is much lower than the other two cases. This was expected from the transmission differences shown in the main text.

Fig. 10. Normalized radiated power of a dipole in SW, DW and DWA systems. The dipole is located 4 \mu m away from the end of the guides at the center of the gap (22.5 nm away from the wire in the case of SW). The power radiated by the dipole in systems DW (black line) and DWA (red line) is practically the same, confirming that the source does not ‘see’ the antennas (as expected for PTLs of this length). The power radiated by the dipole in the SW (blue line) is much lower than the other two cases. This was expected from the transmission differences shown in the main text.
hand, the power radiated by the dipole in the SW system is much lower than the other two cases, as expected from the low SW transmission shown in the main text.

6.6. Antenna resonance

The dimensions of the gap antennas have been chosen to be at resonance (in isolated mode) with the wavelengths of the emission of the QDs. Figure 11(a) shows the spatial intensity distribution of the resonance mode (fourth order mode) that matches the emission of the QDs. When it is fed from the gap the intensity is confined mainly inside it. The overlap between antenna resonance and QD spectrum is shown in Fig. 11(b) where the simulated (FDTD) resonance modes for a gap antenna of these dimensions are plotted. The gray shadow marking the FWHM spectrum of the QD emission overlaps better with the fourth order mode of the gap antenna. It has been shown theoretically that the dimensions which give the resonance in the isolated case are approximately the dimensions for maximum in-coupling efficiency from the far-field towards an infinite waveguide attached to the antenna [41]. Note that, following the reciprocity principle, this will hold also for maximum out-coupling efficiency from the near-field towards the far-field for that particular wavelength. This is important for the experiments described in this work, since the system is driven locally by the QDs and not with the laser from the far-field.

Fig. 11. Simulated resonance behavior of the gap antennas in isolated mode. The height, width and length of each bar is 40 nm, 50 nm and 440 nm respectively. The gap between them is 45 nm. (a) Simulated spatial intensity profile of the fourth order mode of this gap antenna when is fed from the gap. (b) Intensity profile as a function of wavelength for the same gap antenna. The third and fourth order modes are visible (located at wavelengths of 870 nm and 745 nm respectively). The FWHM of the emission spectrum of the QDs is marked in gray showing the overlap with the fourth order mode of the gap antenna.
6.7. Intrinsic impedance of the DW

The second function of the antennas (i.e. to remove or decrease plasmon reflections) is analyzed by calculating the value of the intrinsic impedance of the DW ($Z_0$) used in the experiments and the impedance value of the load attached to it ($Z_L$). The proximity of both impedance values gives the level of impedance matching between both circuit elements. Notice that the intrinsic impedance of the DW is the same as that of the DWA. To calculate the intrinsic impedance $Z_0$, we use a method described in reference [1]. By doing so, the calculated complex $Z_0$ is plotted in Fig. 12. Notice that the impedance of the waveguide seems to undergo a resonant behavior, with a peak of the real part of $Z_0$ (black line) around 810 nm and a phase shift (jump) of the imaginary part (red line) at the same wavelength. This resonance is located around the resonance point for a length of 110 nm. It could be argued that this concurrence could also explain the dip in transmission happening at that wavelength. Indeed, since the polarization of the y-oriented dipole exciting the structure is perpendicular to the PTL, it can easily couple to the width of the wire thus non contributing to the transmission. It would be interesting to further study this possibility by changing the width of the simulated wires and checking the corresponding shift in $Z_0$. This will allow to maximize the transmission of the QD luminescence.

![Fig. 12. Calculated intrinsic impedance ($Z_0$) of the DW.](image)

Fig. 12. Calculated intrinsic impedance ($Z_0$) of the DW. The real part of the intrinsic impedance (black line - left axis) shows a peak at a wavelength of 810 nm around the resonance point of a length of 110 nm (the width of the wires). The imaginary part of the intrinsic impedance (red line - right axis) also experiences a phase jump around the same wavelength. At the maximum of the emission of the QDs (770 nm) the value of the intrinsic impedance is $Z_0=268+10j$.

6.8. Intrinsic impedance of the load

In order to calculate the impedance of the antennas, a plane monitor (XZ-plane) is used parallel to the direction of propagation and passing through the middle of the gap. This monitor allows to record the intensity profile decaying from the source towards the end/antenna at a height of 15 nm inside the gap.
Notice that since the intensity monitor is a longitudinal line cut, it represents an averaged intensity given by the contribution of all the modes present in the gap (around the structure in the case of the single wire). Since the PTLs have a finite length, ending at 4 μm away from the dipole position, the signal reaching the end/antenna will bounce back towards the source. The reflection coefficient (Γ) of the modes arriving to the end of the PTL is related to the impedance of the load (Z_L) attached to it as [52, 53]

\[
Z_L = Z_0 \frac{1 + \Gamma}{1 - \Gamma}
\]  

(10)

Where Z_0 is the intrinsic impedance of the PTL. In order to obtain the value of Γ, hence Z_L, the intensity propagation simulated by FDTD can be fitted using the mode parameters found by BEM calculations. As first step, each of the two modes traveling through the PTL can be described mathematically as

\[
A_i = A_{0i} e^{-\gamma_i x} e^{j\theta_i}
\]

(11)

Where A_{0i}, γ_i and θ_i are the amplitude, propagation constant and phase of the i mode (i ∈ {1, 2}) respectively. The propagation constant is defined as γ_i = α_i + jβ_i, where α_i is the attenuation constant and β_i is the phase constant i.e. the real part of the wave-vector or k_i. Since the distance from the source to the end of the PTL is 4μm, only the modes with large propagation length will reach the end and reflect back towards the source. For those modes, another term accounting for the reflection has to be introduced in the previous equation i.e. \(1 - \Gamma e^{-2\gamma(L_{TL})}\). Where Γ is the complex reflection coefficient and L_{TL} is the length of the PTL. Since, in the three cases under investigation (SW, DW and DWA) only one of the modes has large propagation distance (i.e. the second order mode of the SW and the external mode of the DW/DWA), the total intensity (I_{TOT}) propagating through the system can be described as

\[
I_{TOT} = | \sum_{i=1,2} (A_i)|^2 = |A_{01} e^{-\gamma_1 x} e^{j\theta_1} (1 - \Gamma_1 e^{-2\gamma(L_{TL})}) + A_{02} e^{-\gamma_2 x} e^{j\theta_2}|^2
\]

(12)

With the values of k_\parallel (i.e. β) and L (i.e. (2α)^{-1}) obtained from BEM simulations, it is possible to fit the simulated intensity profile decaying from the source towards the end of the PTL. Accounting for differences between simulation methods, these parameters were allowed to vary in a small range of values. This was shown in Fig. 3 of the main text, where the fit was matching very accurately the simulated intensity. The fitted values obtained for the SW modes at an excitation wavelength of 770 nm are

\[
A_1(SW) \equiv \begin{cases} 
A_{01} = 8.811 \pm 0.138 \text{ V/m,} \\
\alpha_1 = 8.789 \cdot 10^{-5} \pm 6.505 \cdot 10^{-6} \text{ nm}^{-1}, \\
\beta_1 = 0.01254 \pm 2 \cdot 10^{-5} \text{ nm}^{-1}, \\
\theta_1 = 0 \text{ rad,} \\
|\Gamma_1| = 0.1462 \pm 6.1 \cdot 10^{-3}, \\
\theta_{\Gamma_1} = 1.726\pi \pm 9.8 \cdot 10^{-2} \text{ rad} 
\end{cases}
\]

(13)

And

\[
A_2(SW) \equiv \begin{cases} 
A_{02} = 21.73 \pm 0.275 \text{ V/m,} \\
\alpha_2 = 8.749 \cdot 10^{-4} \pm 9.8 \cdot 10^{-6} \text{ nm}^{-1}, \\
\beta_2 = 0.0194 \pm 2 \cdot 10^{-5} \text{ nm}^{-1}, \\
\theta_2 = -0.217 \pm 1.535 \cdot 10^{-2} \text{ rad} 
\end{cases}
\]

(14)

The fitted values for the DW modes at an excitation wavelength of 770 nm are
light ($\lambda_{\text{PTL}}$) is coupled, guided and decoupled out by the system waveguide/antenna. Or two, the laser emission comes from different origins. One, the luminescence of the excited QDs ($\lambda_{\text{em}}=770$ nm) at the center of the PTL. The intensity of the resulting interference mode is plotted in blue and clearly shows that its propagation parameters are not constant and depend on the position.

The fitted values for the DWA modes at an excitation wavelength of 770 nm are:

$$A_{1}(\text{DWA}) \equiv \begin{cases} A_{01} = 12.76 \pm 8.5 \cdot 10^{-2} \text{ V/m}, \\ \alpha_{1} = 2.586 \cdot 10^{-4} \pm 5.4 \cdot 10^{-6} \text{ nm}^{-1}, \\ \beta_{1} = 0.01414 \pm 1.5 \cdot 10^{-5} \text{ nm}^{-1}, \\ \theta_{1} = 0 \text{ rad}, \\ |\Gamma_{1}| = 0.3838 \pm 1.525 \cdot 10^{-2}, \\ \theta_{\Gamma_{1}} = 0.728 \pi \pm 7.7 \cdot 10^{-2} \text{ rad} \end{cases}$$

$$A_{2}(\text{DWA}) \equiv \begin{cases} A_{02} = 95.52 \pm 0.24 \text{ V/m}, \\ \alpha_{2} = 1.287 \cdot 10^{-3} \pm 3 \cdot 10^{-6} \text{ nm}^{-1}, \\ \beta_{2} = 0.02409 \pm 1.5 \cdot 10^{-5} \text{ nm}^{-1}, \\ \theta_{2} = 0.06 \pi \pm 6.9 \cdot 10^{-3} \text{ rad} \end{cases}$$

With the fitted values of $\Gamma_{i}$ the impedance of the load ($Z_{L}$) can be calculated using equation 10. The obtained $Z_{L}$ for the DW and DWA systems are $Z_{L}(\text{DW}) = 154 - 241j$ and $Z_{L}(\text{DWA}) = 135 + 99j$ respectively. For this last comparison, the end of the DW is considered to act as an antenna by itself. Figure 9(a) shows the intensity of each of the modes described above as well as the $I_{\text{TOT}}$ (i.e. intensity of the interference mode) for the three systems SW (up), DW (middle) and DWA (down). Mode 1 (black line) represents the second order mode for the SW and the external mode for the DW/DWA systems. Mode 2 (red line) represents the first order mode for the SW and the gap mode for the DW/DWA. The propagation length for mode 1 is larger than for mode 2, so it creates destructive interferences after reflecting back at the end of the PTL. The intensity of the resulting interference mode is plotted in blue and clearly shows that its propagation parameters are not constant and depend on the position.

### 6.9. Luminescence propagation

Although, as explained in the main text, the dimensions of the DWA are chosen to work better at 770 nm than at 640 nm, the light being propagated through it could be initially of two different origins. One, the luminescence of the excited QDs ($\lambda_{\text{em}}=770$ nm) at the center of the PTL is coupled, guided and decoupled out by the system waveguide/antenna. Or two, the laser light ($\lambda_{\text{exc}}=640$ nm) is directly coupled and guided by the DWA, exciting the QDs at the ends of it where it is decoupled out by the antennas. Notice that the light being detected at the antennas can not be direct laser light coupled out from the DWA due to the two long pass filters (Semrock, LP02-647RU) in the detection path and the clean filter (Semrock FF01-640/14) in
the excitation path. It can also not be the luminescence from the gold itself because of the spectrum measurements shown in the main text. These spectral measurements showed that the light being propagated is the QDs luminescence. In order to further confirm this fact, the properties of this light is further analyzed in the following.

6.9.1. Polarization of the luminescence

Since the detected light can be split by a polarization beam cube into a pair of similar APDs (Micro Photon Device, MPD series), the confocal images can be resolved in polarization. This allows to identify the polarization of the light coming out at the end of a DWA with total length of 5 μm. Figure 13(a) shows the integrated intensity profile (vertical integration of the light inside a similar gray dotted box as in Fig. 5 of the main text) along the waveguide area representing both polarization channels Pol∥, i.e. parallel to the PTL (black line) and Pol⊥, i.e. perpendicular to the PTL (red line). As expected the bright central spot is polarized perpendicular to the PTL (y direction), i.e. being formed by two perpendicular optical axis, the emission of the QDs is partially depolarized when they are excited by a preferential axis (excitation perpendicular to the waveguide, y-axis).

After normalization (Fig. 13(a) inset), the ratio between Pol∥ and Pol⊥ is different at the central spot and at the ends. This is mainly due to the fact that the emission of QD luminescence is done through the antenna fourth order mode which has no preferred polarization direction. It is fair to note that the same result would be obtained for both hypothesis at hand i.e. QDs or laser propagation.

6.9.2. Polarization of the excitation

On the contrary, if the polarization of the laser is rotated 90 degrees with respect to the initial configuration (initially perpendicular to the DWA), some differences would start to appear depending on the nature of the propagating light. In fact, under the hypothesis of the laser light being propagated through the DWA, if the polarization of the laser is parallel to the waveguide, the coupling efficiency towards the DWA will be decreased considerably. As shown in Fig. 3 of the main text for a dipole source, this can be several orders of magnitude lower than for perpendicular polarization due to the mainly perpendicular components of the electric fields involved in the gap and external modes. Thus, even if the central spot will still be very intense (direct excited QDs), the percentage of light at the ends of the guide would be lower.

However as shown in Fig. 13(b), the relative ratio between central and side spots stays the same despite the polarization of the laser (Polexc⊥ (black line) and Polexc∥ (red line)). This behavior confirms the hypothesis of the QDs luminescence being propagated regardless of how they are excited.

6.9.3. Wavelength of the excitation

Another way of confirming this hypothesis is to change the wavelength of the excitation. Since the waveguide is designed to work better at λ=770 nm, if the wavelength of the laser is further from that value, the laser light would not be able to be coupled to the DWA. This means that decreasing the wavelength of the laser from 640 nm (black line) to 532 nm (red line) will decrease even further the coupling efficiency. At the same time, since the QDs absorption band is very broad and goes far into the low optical spectral region, they will still be effectively excited at a λexc=532 nm. As shown in Fig. 13(c), the two spots at the end of the waveguide are still visible confirming the luminescence propagation also for an excitation wavelength of 532 nm.
Fig. 13. Testing the propagation of QDs luminescence. Integrated intensity profiles for DWA systems of 5 μm in length under different excitation or detection conditions. (a) Excited at $\lambda_{\text{exc}}=640$ nm with polarization $\perp$ to the DWA and detection split into $\perp$ (black line) and $\parallel$ (red line) polarizations. (b) Excited at $\lambda_{\text{exc}}=640$ nm with polarization $\perp$ (black line) and $\parallel$ (red line) to the DWA (detection of $\perp+\parallel$ polarizations). (c) Excited at $\lambda_{\text{exc}}=640$ nm (black line) and $\lambda_{\text{exc}}=532$ nm (red line) with polarization $\perp$ to the DWA. (d) Excited at $\lambda_{\text{exc}}=640$ nm with polarization $\perp$ to the DWA before (black line) and after (red line) bleaching of the QDs in the central area. All the test confirm that the QDs luminescence is being propagated through the DWA.

6.9.4. Bleaching of the QDs

Finally, it seems clear now that by removing the QDs, the DWA will stop driving any light. In order to further confirm this, the power of the laser is doubled and the excitation spot is kept fix at the central position on top of the waveguide for 5 minutes. After that time, some QDs are expected to be bleached, in fact, the central peak in Fig. 13(d) shows 6 times more signal before (black line) than after (red line) the bleaching of the QDs. If the luminescence of the QDs is being propagated through the DWA, the two spots at the ends of it are supposed to be 6 times weaker also. On the other hand, if the laser is being propagated through the DWA, the side spots will not suffer any change. Again, the inset in Fig. 13(d) shows that the relative intensity between central and side spots stays the same after the bleaching further confirming the propagation of the luminescence of the QDs through the DWA.
Acknowledgments

The authors thank R. Zia and P. de Roque for fruitful discussions. This work was funded by the European Research Council Advanced Grant 247330 (NanoAntennas), the Spanish MINECO (Grant Nos. CSD2007-046-NanoLight.es, FIS2009-08203, and MAT2014-59096-P) and the Fundació CELLEX Barcelona. A.M. acknowledges financial support from the Department of Physics and Astronomy and the College of Arts and Sciences of the University of New Mexico.