

# Engineering Highly Directive Optical Waveguide Antennas

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## Abstract

We show the numerical and experimental realization of broadband optical traveling-wave antennas made from low-loss dielectric materials which exhibit highly directive patterns. The high directivity is a result of the interplay between two dominant TE- and leaky-modes present in the antenna director. These antennas possess near unity radiation efficiency at the operational wavelength of 780 nm, maintaining a broad bandwidth. We envision that our all-dielectric approach demonstrates a new class of antennas that are excellent candidates for optical-communication and sensing.

## 1. Introduction

Optical antennas provide a promising way to efficiently convert propagating light waves into localized modes and vice versa. The directed emission from these antennas can be used for a multitude of applications, in particular, on-chip communication can utilize different functionalities offered by antennas such as high directivity and front-to-back ratio, good radiation efficiency, low side lobe level, broadband and tunable capabilities, and a compact design [1]. These qualities can be pursued using dielectric structures, which furnish us with reduced dissipative losses and fabrication tolerances in comparison to the metals in the optical regime [2]. In the same context, it has also been shown recently that optical traveling wave antennas which support guided modes in addition to leaky modes exhibit excellent directional characteristics and a broadband nature [3]. The electromagnetic response and overall functionality of these antennas depend on the frequency of operation, structure geometry, material constituting the antennas and footprint of the structure. These enable the control over the modes excited and thus the angular radiation patterns, therefore providing a need for a meticulous designing and optimization strategy [4].

## 2. Results and Discussion

In this work, we report on a comprehensive numerical and experimental analysis of traveling-wave antennas made of different low-loss dielectric materials like hafnium dioxide

(HfO<sub>2</sub>), tantalum-pentoxide (Ta<sub>2</sub>O<sub>5</sub>) and Silicon (Si), furnishing a highly directive emission. Our dielectric antennas consist of two elements, namely, the reflector and director that are placed over a glass substrate. In particular, three different types of directors comprising the rectangular-, horn-, and tip-shaped geometries were designed and optimized. We utilize full-wave numerical simulations, which employ the particle swarm optimization in conjunction with the trust-region algorithm to realize robust antennas with high directive gains. The maximum directive gain (directivity  $D$ ) is used as a cost function and defined as

$$D = \max D(\theta, \varphi) = \frac{4\pi U(\theta, \varphi)}{\int_0^\pi \int_0^{2\pi} U(\theta, \varphi) \sin(\theta) d\theta d\varphi}, \quad (1)$$

where  $D(\theta, \phi)$  and  $U(\theta, \phi)$  are, respectively, the directive gain and angular radiation intensity of the antenna in a direction defined by the polar angle  $\theta$ , measured with respect to the optical axis ( $z$ -axis) and the azimuthal angle  $\phi$ , measured with respect to the antenna axis ( $x$ -axis).

To give a deeper insight into our work, the schematic representation of the numerical setup and orientation of one of the antennas (rectangular-antenna) with respect to the  $xyz$  coordinates is illustrated in Fig. 1a, which also highlights the parameters used in the optimization process. Fig. 1c shows the calculated linear directive gain with tightly focused main lobe pointing at a polar angle of  $\theta = 69^\circ$  and azimuthal angle  $\phi = 0^\circ$  with a high directivity of 63.1. Our study reveals that the directivity and main lobe emission are majorly governed by two guided transverse electric modes that radiate from the end facet of the director. To validate our results, we also fabricated our optimized antenna using a two-step electron-beam lithography, whose scanning electron micrograph is depicted in Fig. 1b. The red box in the image indicates the area of quantum dot (QD) deposition. The measured far field intensity distribution in Fig. 1d is in good qualitative agreement with the numerical calculations. However, some discrepancies are observed in higher polar angles which can be attributed to the displacement of the quantum dots from the optimal position as well as the limited collection angle of the setup. Additionally, the ring-like feature at around  $\theta = 41^\circ$  stems from uncoupled QDs emitting directly into the substrate in all

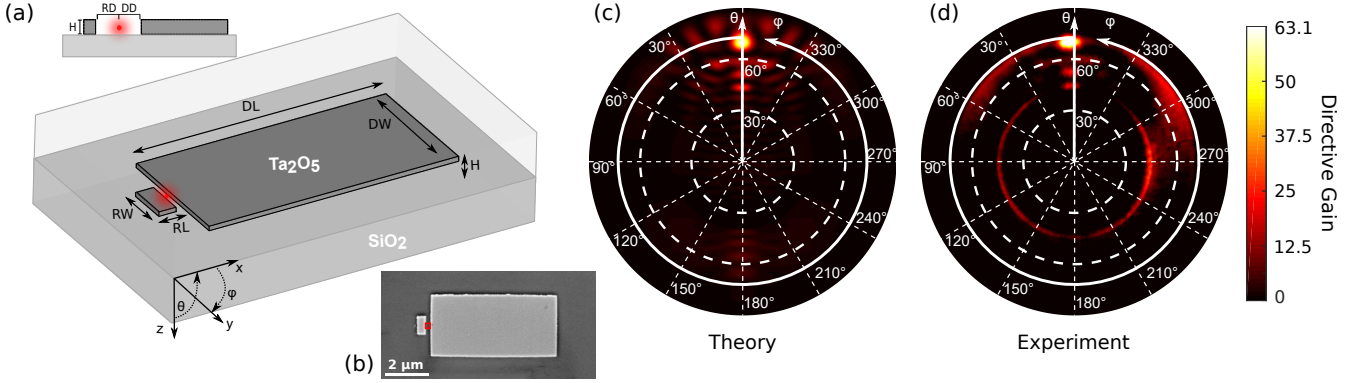


Figure 1: (a) Schematic representation of the  $\text{Ta}_2\text{O}_5$  rectangular-antenna, highlighting the parameters used in the optimization. The antenna is excited by a dipole source emitting at 780 nm (red spot). (b) Scanning electron micrograph of the optimized antenna design with the red square marking the region of deposited QDs. (c) Calculated angular linear directive gain distributions of the antenna exhibiting an in-plane directivity of  $D = 63.1$  at  $\theta = 69^\circ$ . (d) Measured far-field intensity normalized to theoretical maximum.

azimuthal angles. A similar nature with a further enhanced performance is observed in the other antennas investigated in the scope of this work. These antennas are not just ultra directive, but they also showcase high efficiency and a wide operating frequency range while being robust with respect to fabrication tolerances. Furthermore, they also offer an opportunity to tailor the directivity and main lobe angle [4].

### 3. Conclusions

We present a series of optimized guided-wave optical antennas exhibiting high directivity. The antennas consist of a dielectric reflector and a director lying on a glass substrate, and a dipole emitter, placed in the feed gap between them serves as the source of excitation. In particular, we analyzed antennas with rectangular-, horn- and tip-shaped directors made of different low-loss dielectric materials. Our analysis of the optimized antennas reveals that their light emission is predominately governed by two TE guided modes in the director and show high linear directivity over a wide wavelength range. Our findings demonstrate the uniqueness and robustness of these optical antennas, which renders them excellent candidates for sensing applications and optical interconnects.

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