



# Nanoplasmonic directional couplers and Mach–Zehnder interferometers

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## ABSTRACT

We present a novel design and analysis of two nano-scale plasmonic devices: a directional coupler and a Mach–Zehnder interferometer. The designs of the two devices are based on our recent work on the air-gap coupler that resulted in high coupling efficiency between a dielectric waveguide and a plasmonic waveguide. The two devices are embedded between two dielectric waveguides and operate at optical telecom wavelengths. The overall efficiency was 37% for a 2 × 2 directional coupler switch and above 50% for the proposed designs for a Mach–Zehnder interferometer. The efficiency in the proposed devices can be increased using broader plasmonic waveguides.

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## 1. Introduction

Surface plasmon polariton (SPP) occurs at the interface between metal and dielectric material due to the interaction between the free surface electrons with the incident photons [1–3]. Thus, light can be confined in ultra small dimensions. To confine light further in the dielectric region, the dielectric region is put between two metals. In this configuration, the decaying SPP mode at each dielectric–metal interface interacts with the other, creating a confined light in the dielectric region. The dielectric width can be far below the diffraction limit because as the dielectric width decreases the effective refractive index increases. Reducing the width of the dielectric region improves the mode confinement and decreases the propagation length [4,5]. The propagation length is decreased because as the mode confinement increases, the interaction with metal increases and consequently the losses increase.

Several different optical circuit elements and devices such as directional couplers [6–8] and Mach–Zehnder interferometers (MZIs) [8,9] have been proposed because they are considered as the platform for the optical sensors. To the best of our knowledge none of the proposed directional couplers and MZIs in the literature has dealt with the coupling from a dielectric waveguide into a plasmonic waveguide and back into the dielectric waveguide,

which is taken into consideration in our work. It is necessary to use dielectric waveguides to connect the plasmonic devices to the light source and detector so that the propagation losses due to the metallic interaction are dramatically reduced. The size of the directional coupler depends on the separation distance between the two adjacent waveguides, widths of the waveguides, the refractive index of the waveguides, the refractive index of metal, and the operating wavelength. Zia et al. [4] found that negligible cross talk between two adjacent metal–dielectric–metal waveguides occurs when the separation distance between the two waveguides is greater than 150 nm. Traditional dielectric directional couplers are used as splitters in which there is a 90° phase shift between the two split beams. A different phase behavior occurs in metal–dielectric–metal directional couplers in which the phase difference between the two split beams is less than 90° [9]. Wang and his co-worker [9] attribute this phase behavior to the interaction of the field with the complex refractive index of metal. Unlike traditional dielectric directional couplers, plasmonic directional couplers have wavelength coupling dependence because the real part of the complex refractive index of metal changes as wavelength changes [7].

In our previous work [10,11], we proposed a direct yet efficient short plasmonic air-gap coupler (AGC) to increase the coupling efficiency between a silicon waveguide and a silver–air–silver plasmonic waveguide. We also proposed a splitter that delivers light from a silicon waveguide into two plasmonic waveguides achieving a coupling efficiency of 45% for each branch. In this work, we present two potential applications of our proposed coupler and splitter: a directional coupler and a Mach–Zehnder interferometer.

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