Optics Communications 382 (2017) 119–126

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Enabling inter- and intra-chip optical wireless interconnect by the aid of hybrid plasmonic leaky-wave optical antennas

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A R T I C L E I N F O

Article history:
Received 5 April 2016
Received in revised form
8 July 2016
Accepted 13 July 2016

Keywords:
Photonic Integrated Circuit (PIC)
Optical link
Hybrid plasmonic
Leaky-wave antennas
Optical antennas

A B S T R A C T

In this paper, we propose a new method to provide optical link in Photonic Integrated Circuits (PICs). The proposed method uses two hybrid plasmonic leaky-wave optical antennas, operating at the standard optical telecommunication wavelength of 1.55 μm, to provide inter-chip interconnect between two layers in a photonic chip and also intra-chip interconnect between two different photonic ICs. Linearly tapered couplers are designed to couple the optical signal from the silicon waveguide to the hybrid plasmonic antennas. The performance of the proposed optical link is verified using numerical full wave simulation. The proposed structure is planar, and can be fabricated using standard CMOS technology which makes it the superior candidate for realization of future multi-layered Photonic Integrated Circuits.

1. Introduction

Recently developing Photonic Integrated Circuits (PICs) have attracted different research groups around the world due to their great advantages over electronic ICs including high speed, high bandwidth, and low power consumptions [1–7]. Due to the increased demand for high rate data processing, developing optical links with high rate of data transfer is inevitable.

To provide optical interconnect between two layers in a PIC or between two different photonic ICs, researchers have proposed several different methods including polymer waveguide [8], fiber ribbons [9], fiber image guide, and free space methods [10–12]. Among the proposed methods, the waveguide based methods could be used to provide only an inter-chip interconnect between different parts of an integrated circuit in the same layer. Although, the free space methods could be used both as inter- and intra-chip interconnect, these methods use 3D structures such as lenses and mirrors [10–12] which can't be integrated easily with other planar elements in a photnic integrated circuit. Moreover, these 3-dimensional structures are bulky which is another challenge when using them in a compact integrated circuit.

In this paper, using optical plasmonic antennas, we propose a new planar structure to provide optical links in photnic integrated circuits. The proposed method can be used for inter-chip communication between different layers of a multi-layered PIC or to provide intera-chip wireless interconnect between two PICs. The most important advantage of the proposed structure over the previously reported works is its compactness and planar structure which permits to fabricate it in the same process used in fabrication of the PIC itself. This new and compact optical link can be a promising candidate to be used in future optical computers.

In this method, two leaky-wave optical antennas are used as transmitter and receiver components. Recently, optical antennas have received significant attention due to their ability to control the light emission within a nano-scale footprint [13–26].They have been used for different applications such as near-field sensors [27], optical imaging [28], higher harmonic generation [29], and sensing. The optical antenna used in this method lies in the category of traveling wave antennas in which a guided mode is converted to a radiation mode through periodic discontinuities in the structure [30–36]. Traveling wave antennas have advantages of higher directivity and wider bandwidth when compared to resonant antennas [37–39], resulting in higher data rate and higher efficiency when used in a wireless optical interconnect.

The device proposed here is designed based on hybrid plasmonic structures in which a dielectric with lower refractive index is sandwiched between a metal and a dielectric with higher refractive index [40–46]. Hybrid plasmonic structures have the advantages of lower loss when compared to pure plasmonic structures, and higher field confinement when compared to dielectric structures [40–46]. Here we have preferred vertical slot scheme, supporting TM mode, for our device over horizontal schemes [47,48], supporting TE mode, due to the advantages that vertical

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http://dx.doi.org/10.1016/j.optcom.2016.07.037
0030-4018/

scheme provides in this application. These advantages include higher field confinement which avoid field distortion by other layers or devices, and the ability of easy discontinuity generation just by adding slots in the metallic layer.

The organization of the paper is as follows: first the leaky-wave optical antenna is designed and its performance for operation at the standard telecommunication wavelength of 1550 nm is numerically verified. Then, a linearly tapered coupler is designed to efficiently couple the optical signal from a silicon waveguide to the hybrid plasmonic antenna and vice versa. Finally a multi-layered photonic IC is designed in which the proposed antennas in conjunction with couplers are used on different layers of the integrated circuit to provide an inter-chip optical link. The performance of the proposed antennas to provide intera-chip interconnect between two different photonic ICs is also investigated through numerical analysis.

2. Hybrid plasmonic leaky-wave optical antenna

The designed leaky-wave optical antenna is shown in Fig. 1. The periodic slots along the hybrid plasmonic waveguide transform the fundamental propagating mode of the waveguide to the radiating mode of the antenna. The antenna is designed based on hybrid plasmonic structures which consists of a thin layer of SiO_2 sandwiched between silver and silicon. Since the refractive index of silicon is greater than that of SiO_2 and the permittivity of siliver is negative in the standard optical communication wavelength of 1.55 µm, the supported optical mode will be confined inside the thin SiO_2 layer [40–46].

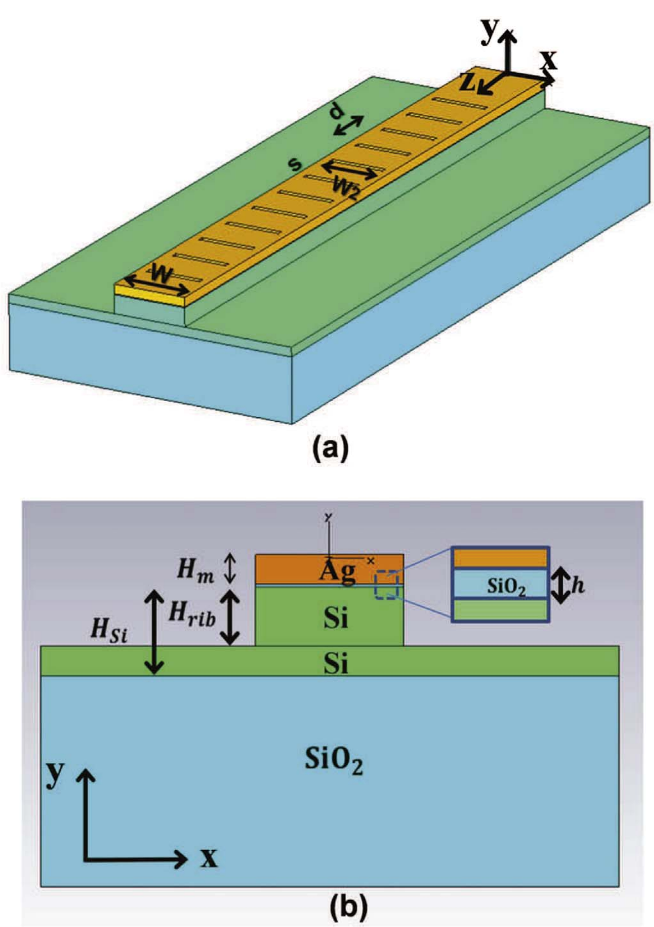

Fig. 1. Schematic of the leaky-wave optical antenna (a) Perspective view (b) Side view.

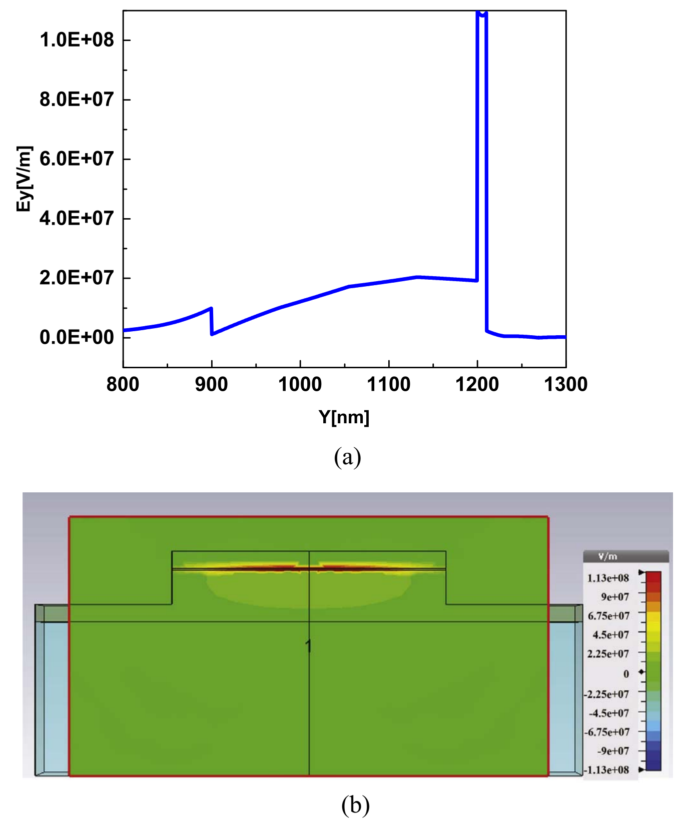

Fig. 2. Numerically calculated *y* component electric field at the cross-section of the hybrid plasmonic waveguide (a) 1D result, (b) 2D result.

According to the theory of surface plasmons, only TM modes could be supported by these hybrid plasmonic structures [49–51]. Therefore the electric field inside the antenna has both *y* and *z* components. However, as shown in [52], the *z* component of electric field is much smaller than the *y* component and could be neglected in this analysis. To numerically verify this fact, in Figs. 2 and 3, we have compared the electric field components at the cross-section of a hybrid plasmonic waveguide with dimensions of $W = 1600$ nm, $h = 10$ nm, $H_{si} = 300$ nm, and $H_m = 100$ nm. The results shown in this figure are obtained using full wave numerical analysis carried out in CST microwave studio. In this analysis, the material parameters used in the structure are as follows: the refractive index of SiO_2 and Silicon are considered as 1.44, and 3.42 respectively, and for the Silver we have used the experimental data reported in [53] which takes the frequency-dispersion and also loss of this material into account. As the results of Figs. 2 and 3 show, the *y* component of the electric field is one order of magnitude bigger than the *z* component, and also the *y* component is highly confined inside the thin SiO_2 layer ($1200\ \text{nm} < y < 1210\ \text{nm}$) verifying the excitement of the hybrid plasmonic mode inside the waveguide. Based on the modal analysis of the hybrid plasmonic waveguide, its propagation lenght is equal to $L_p = 130.6$ µm.

Neglecting the *z* component and using the Floquet theorem, E_y could be expressed in terms of Fourier series as [54]:

$$E_y = \sum_{n=-\infty}^{\infty} E_{y,n} e^{-jK_{z,n}z},\ K_{z,n} = -j\alpha + \beta_{z,0} + 2n\frac{\pi}{d} \tag{1}$$

where n , $E_{y,n}$, $K_{z,n}$, α, $\beta_{z,0}$, and d are order of Fourier component, the magnitude of *nth* order, the wavenumber of the *nth* component, the attenuation constant of the structure, the wavenumber of the fundamental mode of the hybrid plasmonic waveguide and the