



Integration of silicon-loaded nanoplasmonic waveguides onto a micro-machined characterization beam for nonlinear optics applications

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ABSTRACT

Silicon-loaded nanoplasmonic waveguides were integrated onto a micron-scale characterization beam to allow for accurate and efficient nonlinear optical characterization. The waveguides consist of a $95 \text{ nm} \times 340 \text{ nm}$ silicon core that is capped by a 60 nm thick gold film. The characterization beam is formed by precision cleaving one waveguide end facet and by deep silicon etching the substrate area adjacent to the other end facet. This configuration allows input radiation to be coupled directly to the waveguides using a microscope objective and output radiation to be out-coupled with a lensed single-mode optical fiber. The fabrication steps are characterized via scanning electron microscopy at various points throughout the process. The fabricated devices are optically characterized using an ultrafast nonlinear pump–probe time-domain spectroscopy setup. Ultrafast all-optical modulation is measured in the waveguides on two timescales: $\tau_1 = 1.98 \pm 0.40 \text{ ps}$ and $\tau_2 = 17.9 \pm 6.8 \text{ ps}$.

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1. Introduction

Fiber optical networks have proven to outperform electrical networks in bandwidth and energy consumption. This success has motivated substantial effort into developing chip-scale photonic waveguide circuits. Silicon (Si) photonic devices fabricated on silicon-on-insulator (SOI) substrates have reached a sophisticated level of development and their integration with complementary metal–oxide–semiconductor devices is undergoing rapid development. As such, optical interconnects have been proposed as a means to alleviate resistive–capacitive delays in the present electrical scheme [1]. While photonic waveguides show promising applications, their minimum cross-sectional dimensions are limited by the light wave diffraction limit. However, for high integration density applications when the separation between waveguides is reduced to the order of a wavelength, photonic waveguides exhibit prohibitive cross-talk due to mode coupling. Furthermore, sharp bends in photonic waveguides result in radiation losses of the propagating optical mode. All of these factors limit the maximum integration density achievable with photonic waveguides.

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Plasmonic waveguides function in a similar manner as photonic waveguides, but incorporate low-loss metal (Au, Ag, Al, and Cu) features. When an appropriate coupling scheme is used, free-space radiation can excite an electromagnetic mode at the interface between metallic features and adjacent dielectric materials. The incident radiation couples strongly to the conduction electrons of the metal and the mode propagates as a coupled oscillation of charge density in the metal and evanescent electromagnetic fields in the dielectric. The strong coupling of radiation to the metal features has enabled demonstration of waveguide devices with cross-sectional dimensions as small as a few tens of nanometers [2]. Plasmonic waveguides also exhibit low cross talk and low bending losses compared to their photonic counterparts.

Along with the aforementioned characteristics, this strong confinement produces an enhancement in the amplitude of the electric field in the vicinity of the metal features. In the case of a nanoplasmonic waveguide, fields can be enhanced by several times their original strength. The enhanced fields can be used to magnify light–matter interaction processes, such as chemical detection [3] or nonlinear optical processes [4,5]. While plasmonic waveguides have several attractive characteristics, strong interaction of the radiation with metals results in propagation losses that are higher than photonic waveguides. The characteristic propagation length of electromagnetic energy in a subwavelength plasmonic waveguide depends strongly on the materials and design of the waveguide and may range from several microns to several tens of

microns. Long-range surface plasmon polariton waveguides have dimensions larger than the optical wavelength, but enable light propagation over millimeter length scales [6,7].

Coupling radiation into nanoplasmonic waveguides with micron-scale lengths requires a carefully designed on-chip coupler, which may add additional fabrication complexities [8,9]. Previous coupling schemes have incorporated prisms [10], photonic bus waveguides [11], gratings [12], plasmonic antennas [13], and nano-mirrors [14] to direct the free-space radiation to the nanoplasmonic waveguide mode.

However, a key predicament in accessing ultrafast active operation in a Si-nanoplasmonic waveguide device is the ability to couple the optical signal directly into the device. That is, when considering nonlinear optical interaction effects in Si-based nanoplasmonic waveguides, it is not possible to achieve efficient nonlinear interaction in the plasmonic region, as nonlinear interaction can occur within the on-chip coupler. End-fire coupling radiation directly into the nanoplasmonic waveguide would eliminate the need for a coupler, but requires separation of the substrate into micron-scale die, which would make subsequent handling and characterization prohibitively challenging. Moreover, these dimensional constraints push traditional die separation techniques, such as dicing or scribing beyond their prescribed abilities. Therefore, it would be beneficial to develop a means to integrate nanoplasmonic waveguides with lengths of several microns onto a macroscopic die in a configuration that would allow their end-facets to be directly accessed with macroscopic objects such as microscope objectives and optical fibers. Realization of such a sample would enable efficient access to nonlinear optical effects and ultrafast modulation in Si-loaded nanoplasmonic waveguides.

In this work, we fabricate Si-loaded nanoplasmonic waveguides and integrate these structures onto a micron-scale “characterization beam.” This characterization beam allows for direct coupling to the waveguides using microscope objectives and optical fibers and enables accurate measurements of ultrafast nonlinear interactions taking place in the waveguide.

2. Device design

The waveguide geometry consists of a Si waveguide core with cross-sectional dimensions, $w \times h = 95 \text{ nm} \times 340 \text{ nm}$. The Si core is capped by a gold (Au) film of a thickness, $t = 60 \text{ nm}$. The cross-sectional geometry of the waveguide is depicted schematically in Fig. 1(a) and the corresponding nanoplasmonic mode profile was obtained with an electromagnetic mode solver and is shown in Fig. 1(b). The theoretical distance propagated by the mode before attenuating to e^{-1} of its initial amplitude was found to be $L_{prop} = 3.1 \mu\text{m}$. In order to ensure a strong signal is transmitted through the device, we consider waveguides with lengths, $L \leq 10 \mu\text{m}$.

A schematic depiction of several nanoplasmonic waveguides integrated onto the characterization beam is shown in Fig. 1(c). In this design, the width of the characterization beam is increased in steps, allowing the waveguide length to be varied. As labeled in Fig. 1(c), one face of the characterization beam is defined by cleaving the SOI wafer and the other is defined by deep etching the Si handle wafer. A deeply etched line is used to define the cleavage plane, ensuring that the cleave intersects the waveguide end-facets. The implementation of this technique is discussed further in Section 4. Notably, a cleaved facet allows for a bulky microscope objective to be brought in close proximity to the sample for excitation. We consider etching depths, $d_{etch} = 75 \mu\text{m}$, allowing for an optical fiber to be brought over the substrate to the output facet of the waveguide. The proposed excitation and detection scheme is depicted schematically in Fig. 1(c).

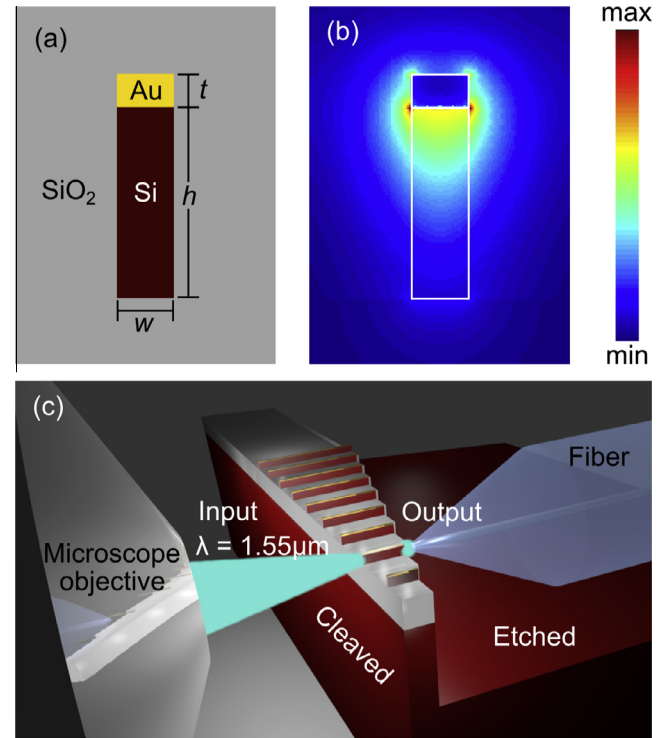


Fig. 1. (a) Schematic of the cross-sectional geometry of the nanoplasmonic waveguide. (b) Distribution of electric field amplitude in the nanoplasmonic waveguide. (c) Schematic of nanoplasmonic waveguides integrated onto a characterization beam, along with the microscope excitation and optical fiber detection configuration.

3. Nanofabrication

3.1. Nanoplasmonic waveguide definition

In order to maintain compatibility with Si photonic devices, we used a SOI substrate with a device layer thickness, $t_{dev} = 340 \text{ nm}$, a buried oxide layer thickness, $t_{BOX} = 1 \mu\text{m}$, and an overall substrate thickness, $t_{sub} = 500 \mu\text{m}$. The fabrication process involved two layers of electron beam lithography (EBL), which were performed using a Raith 150-TWO system.

Organic contamination was removed from the sample by placing it in an ultrasonic bath of acetone for 10 min, followed by a 15 min immersion in Piranha solution (3:1 mixture of 96% H_2SO_4 to 30% H_2O_2). The native oxide was removed by a 45 s bath in buffered hydrofluoric acid (1 HF:10 NH_4F). A schematic depiction of the bare SOI substrate is shown in Fig. 2(a).

In preparation for the first layer of EBL, a layer of 6% 495 K poly(methyl methacrylate) in anisole (495 k PMMA A6) was spun onto the substrate at 5000 rpm (RPM), producing a resist thickness of $t_{PMMA,1} = 275 \text{ nm}$. The sample was then baked at 180°C for 15 min. The pattern was exposed using an aperture diameter, $d = 20 \mu\text{m}$, an acceleration voltage, $V = 20 \text{ keV}$, and an area dosage, $D = 450 \mu\text{C}/\text{cm}^2$. The sample was developed in a methylisobutylketone (MIBK)-based developer (1 MIBK:3 isopropyl alcohol (IPA)) for 45 s. Four subsequent thin films were deposited on the sample using an electron beam evaporation system. The first layer was a $t_{Cr,1} = 5 \text{ nm}$ chromium (Cr) adhesion layer. The second was a $t_{Au} = 60 \text{ nm}$ Au layer, which gives the waveguide its ability to guide optical signals at sub-diffraction dimensions. The third was an additional $t_{Cr,2} = 5 \text{ nm}$ Cr adhesion layer, and the final layer was a $t_{\text{SiO}_2,1} = 40 \text{ nm}$ SiO_2 layer, which acted as an etch mask to prevent sputtering of the soft Au features during subsequent plasma

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