Planar long range surface plasmon waveguides based on ultrathin freestanding metal-composite membranes or membrane strips

Zoran Jakšić, *Senior Member, IEEE*, and Jovan Matović

Abstract — **We propose a novel geometry for the optical waveguides for passive integrated photonics application. Instead of utilizing metal membranes or strips immersed into polymer we utilize freestanding ultrathin metal-composite membranes. Our structures ensure a full symmetricity of the guides and thus minimized losses. We fabricated our experimental freestanding ultrathin membranes utilizing microsystem technologies by applying a proprietary procedure. The fabricated structures are (5-20) nm thick and have an aspect ratio in excess of 500,000.**

Keywords — **Integrated Optics, Nanomembranes, Nanophotonics, Plasmonic Devices, Polaritons, Optical Waveguides, Surface Plasmons.**

I. Introduction

Optical waveguides and various waveguide-based input-output passive and active integrated photonic components play an essential role in broadband optical communications. The conventional planar optical waveguide structures include dielectric and semiconductor guides fabricated by planar technology and microfabrication.

The advent of plasmonic technology ensured the appearance of a new class of planar optical waveguides, with the operation based on the propagation of surface plasmons-polaritons (SPP) [1-3]. Basically, these are either thin metal strips sandwitched between two dielectrics or a dielectric between two metal strips. Their main advantages include extremely short length scales convenient for miniaturization of photonic circuitry and production of ultra-compact devices [1], large field enhancements (up to several orders of magnitude) which enable the use of nonlinear materials [2] and the possibility to use the same metal structure both for optical waveguiding and for the transmission of the controlling low-frequency electrical signals [3]. Since the response of plasmonic waveguides is very sensitive to the metal surface features, micro/nanostructuring of these waveguides ensures a tool to implement efficient tailoring of the desired plasmon propagation [4].

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One of the problems in waveguides with conventional SPP is large signal attenuation, which is a consequence of a high imaginary part of the propagation constant due to the ohmic losses/absorption in metals [4]. In such waveguides the propagation length are typically limited to a range from tens (visible range) to hundreds of micrometers (near infrared). Another problem is their coupling with propagating modes in optical fibers, since typically elaborate schemes using e.g. prism couplers or diffractive gratings must be used.

The way to overcome all of these shortcomings is to use long-range (LR) surface plasmon polaritons [5-8]. These are SPPs which propagate along metal strips with nanometric thickness (typically 10-40 nm) immersed into dielectric, i.e. the profile of their relative dielectric permittivity is fully symmetrical along the propagation axis. In this configuration the field concentration is much lower in the metal sheet and the propagation losses are consequently much lower. The imaginary part of their propagation constant being approximately zero, the LR SPP ensure much larger propagation paths, typical propagation losses being below 6 dB/cm [9]. In addition to that, the LR SPP waveguide dimensions can be tailored to match the field distribution in the optical fiber, thus ensuring a high efficiency of the end-fire coupling of these guides with fibers with losses about 0.5 dB [10].

A number of passive components for integrated optics based on LR SPP and intended for the telecommunication wavelength range have been reported, including straight and bent waveguides, splitters, directional couplers, switches, modulators, etc. [10-12].

There are two main causes for signal attenuation in these structures: one of them are deviations from symmetricity and the other one are losses in cladding material [13]. In order to decrease losses in LR SPP guides, various strategies have been proposed, for instance the use of polymer immersion [13].

In this paper we introduce a new structure for planar LR SPP optical waveguides, based on the freestanding ultrathin metal-composite membranes. Such membranes were first fabricated in ISAS [14-16]. The replacement of the conventional dielectric by air avoids cladding losses and ensures full structural symmetry.

In the context of SP optical waveguides, literature mentions only dielectric nanomembranes as supports for metal strip guides, e.g. [17, 18]. In spite of obvious advantages of the setup, we did not find any previous works related to freestanding metal or metal-composite guides, probably because the field of nanomembranes itself is very new.

In this work we outline the basic idea and theoretical foundations for our approach, present our experimental results, draw some conclusions and point out to possible directions for the future work.

II. Theory

Surface plasmons polaritons (SPP) are TM-polarized surface waves propagating along a metal–dielectric interface at optical frequencies (Fig. 1). Their wavelengths are extremely short and may even enter the X-ray range [2]. The SPP are evanescent both toward the environment and toward the metal layer. In the situation when substrate and superstrate dielectrics differ, the dispersion relation will allow two different modes of propagation, one on each interface [4].

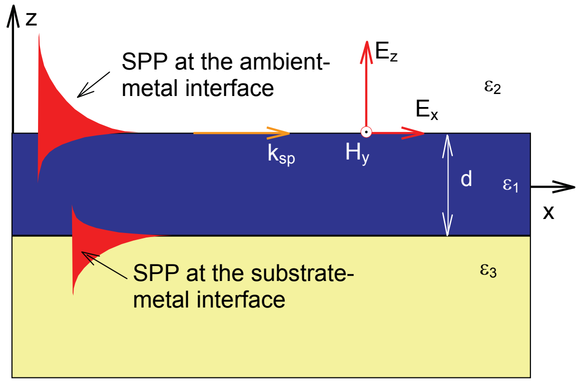

Fig. 1. Basic configuration of a guide for surface plasmon polariton propagation (metal-dielectric interface)

In the case when the substrate and the superstrate are described by identical permitivity (the case of full immersion of the metal sheet in homogeneous dielectric), the structure becomes symmetrical. The two propagating modes on the top and bottom surface degenerate into a single mode (Fig. 2 top).

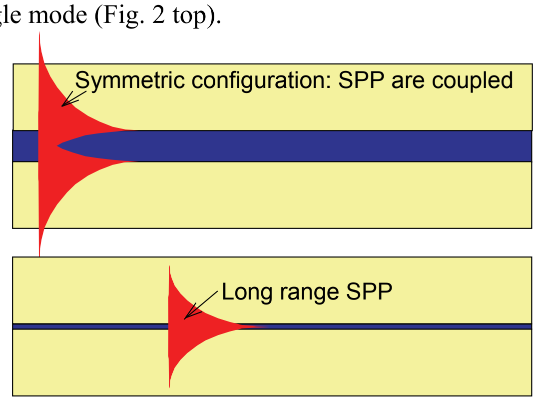

Fig. 2. Generation of long-range surface plasmons polaritons through coupling of top and bottom modes on ultrathin metal sheets; top: metal guide is surrounded from both sides with identical dielectric; bottom: metal sheet is smaller than the decay length and LR plasmon appears

In the case when the metal sheet between two identical media becomes suficiently thin that the interaction between the top and the bottom SPR become non-negligible, these two modes couple and merge into a single mode. The degeneracy for that mode is then removed and its dispersion splits into two branches, one for low-frequency mode (odd), and the other for high-frequency mode (even). The even modes have a very short propagation path and are thus neglected. However, the propagation constant of the odd modes decreases, being proportional to the square of the film thickness. This means that the attenuation of the odd mode will be very low and thus its propagation length large. Thinner films and more symmetrical structures will have longer propagation paths.

Our freestanding nanomembrane may be described as an ultrathin metal or metal-composite film with complex relative permittivity ε_1 and a thickness d situated between two dielectric semi-infinite spaces (filled with liquid or gas, for instance air) with purely real permittivity ε_2. This is the situation depicted in Fig 2 bottom.

The structure is fully symmetrical, with two identical metal-dielectric interfaces where each interface sustains surface plasmon polaritons. Since metal thickness is smaller than the decay length of the modes propagating along the interface, the SPPs are coupled and a long range plasmon system is formed. The symmetricity enables phase matching between the SPP modes at the top and at the bottom interface.

The dispersion relation for SPPs on our structure is obtained by writing the Maxwell equations for low-order TM modes and imposing the boundary condition regarding the continuity of the fields

$$k_1^2 = \beta^2 - k_0^2 \varepsilon_1 \tag{1}$$

$$k_2^2 = \beta^2 - k_0^2 \varepsilon_2 \tag{2}$$

$$\frac{\frac{k_1}{\varepsilon_1} + \frac{k_2}{\varepsilon_2}\left(\frac{k_1}{\varepsilon_1} + 1\right)}{\frac{k_1}{\varepsilon_1} - \frac{k_2}{\varepsilon_2}\left(\frac{k_1}{\varepsilon_1} + 1\right)} = \exp(-2k_1 d) \tag{3}$$

which can be forther written as

$$\tanh \frac{k_1 d}{2} = -\frac{k_2 \varepsilon_1}{k_1 \varepsilon_2} \tag{4}$$

for odd modes which represent long range SPPs. For even modes the right hand term of the above equation has the reciprocal value. Thus the dispersion relation branches into two modes, one of them being quickly attenuated and the other supporting LR SPP waveguiding modes.

The structure itself is extremely simple, which has its obvious advantages in more straightforward microfabrication procedure. It consists of a freestanding nanomembrane supported by silicon rim aligned with fibers in endfire configuration. A sketch of the configuration is shown in Fig. 3.

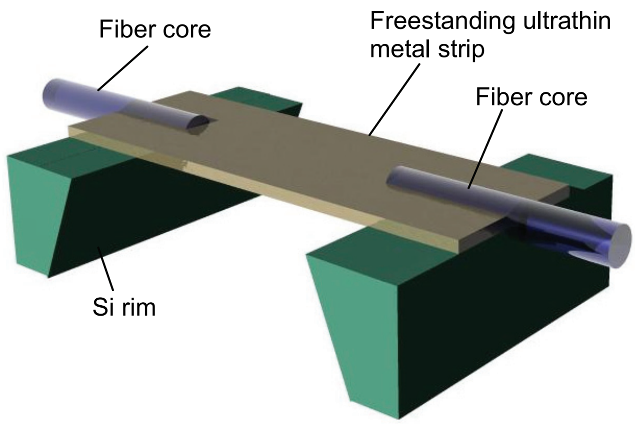

Fig. 3. Freestanding nanomembrane-based LR SPP configuration in endfire coupling setup. The drawing is not to scale.

III. Experimental

The complete procedure for the fabrication of metal-composite nanomembranes with a giant aspect ratio is described in more detail in [15]. Here we outline only the most important steps.

To fabricate our metal-composite nanomembranes we started from single crystal silicon wafers. After the standard preparation procedure we delineated square windows in the photolithographic masks and utilized conventional bulk micromachining to fabricate silicon diaphragms 20-40 μm thick. Each diaphragm had a silicon rim to serve as a support for our structure.

The next step was to use radiofrequent sputtering to deposit a (5-20) nm thin metal-composite layer onto the silicon diagram. To ensure the desired composition of the deposited layer sputtering was done in oxidizing or nidritizing atmosphere.

The next step was complete removal of the Si diaphragm by bulk micromachining which was thus used as a sacrificial structure. A very important step in the procedure is releasing the nanomembrane from the etching solution which must be done very carefully.

After the nanomembrane is fabricated and released it is very robust and actually allows handling with little or no extra precautions. The silicon rim even allows for handling the freestanding nanomembrane by holding the edges with bare fingers. The maximum nanomembrane areas were up to a few cm^2 and the aspect ratios in excess of 500,000 [15] In this manner, although metal-composite nanomembranes belong to nano-objects due to their thickness, they simultaneously belong to macroscopic objects and allow easy manipulation..

It is interesting to mention that this procedure can be used to fabricate nanomembranes in a variety of different metals composites. The membranes for LR SPR guides can be made either into planar sheets or narrow strips.

The thickness of the nanomembranes was checked in a straightforward manner by placing them on a highly polished silicon single crystal wafer and subsequently measuring the thickness using a profilometer device (Talystep).

Besides being fabricated as the "naked" metal-composite structures, our nanomembrane can be additionally laminated with nanometer-thick pure metal layers which are deposited on both surfaces (e.g. gold layers), in this way ensuring a wider range of possible materials for the waveguides and still lower losses in the metal part of the guide.

IV. Results

Fig. 4 shows a calculated curve of attenuation for a metal nanomembrane immersed in dielectric. It is visible that even very small deviations from symmetricity introduce large losses into the waveguide. The losses are much larger for thicker metal sheets and the influence of asymmetry is then much more pronounced.

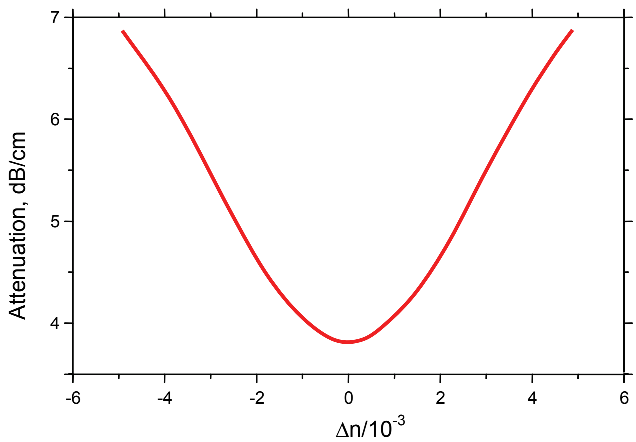

Fig. 4. LR-SPP propagation loss versus asymmetricity of dielectric given as the refractive index difference. Membrane thickness 12.5 nm, material gold, refractive index of dielectric immersion 1.5, wavelength 1.55 μm.

A scanning electron microscope micrograph of the edge of a fabricated nanomembrane is shown in Fig. 5. Very smooth features are clearly visible. The nanomembrane is intrinsically stretched and taut over the silicon rim, ensuring its flatness in nm-range.

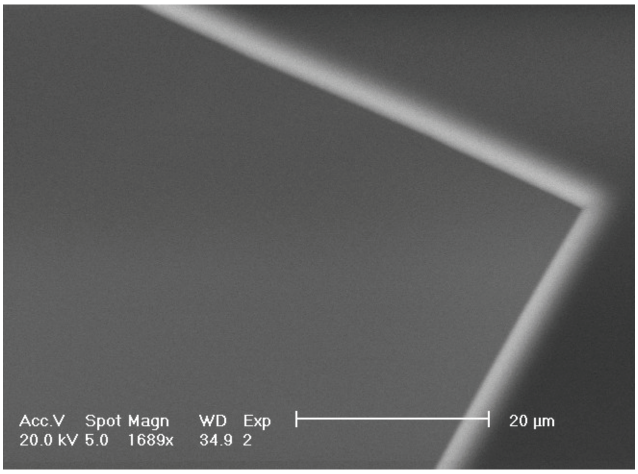

Fig. 5. Scanning electron microscope photo of the edge of a fabricated metal-composite nanomembrane, thickness 20 nm, side length 5 mm.

V. Conclusion

We proposed and fabricated novel structures for long range surface plasmon polaritong waveguides for integrated optics. Our structures ensure a full symmetricity of the guides and thus minimized losses. The minimum guide thickness we are able to fabricate is below 5 nm, which also ensures lower signal attenuation.

The characterization of the proposed waveguides is currently under way and includes their coupling with the propagating waves utilizing end-fire coupling technique through optical fibers and the measurement of their spectral characteristics. As a further step we intend to implement various ways of structuring and sculpting of the nanomembrane surfaces in order to tailor the propagation characteristics and to ensure the functionalities convenient for novel passive devices. The particular structures to be utilized include subwavelength aperture arrays, lamelar membrane multilayers, and incorporation of metamaterial building blocks (e.g. split ring resonators, cut wire pairs and their Babinet counterparts, etc.)

Acknowledgment

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