CHIN.PHYS.LETT. Vol. 24, No. 6 (2007) 1626

Long-Range Surface Plasmon Polaritons Guided by a Thin Metal Stripe *

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(Received 21 December 2006)

A long-range surface plasmon polariton (LRSPP) waveguide consisting of a 15 nm thick gold stripe embedded in a homogeneous polymer BCB is reported. LRSPPs are excited by TM-mode input light successfully using an end-fire method. By scanning the output coupling fibre, the near field of the LRSPP is measured. The propagation loss of as low as 2.34 dB/mm is demonstrated.

PACS: 52. 35. Hr

Surface plasmon polariton (SPP) is a kind of transverse-magnetic surface electromagnetic excitation that propagates in a wave-like fashion along the interface between a metal and a dielectric medium, and whose amplitude decays exponentially with increasing distance into each medium from the interface.[1,2] For a thin metal film surrounded by two semi-infinite dielectrics, the SPPs on the two interfaces couple and form four types of different modes. One of them called the long range surface plasmon polariton (LRSPP) have attracted great attention because its transmission loss decreases with the film thickness[3−5] and it can be excited efficiently by the so-called end-fire method.[4−7] LRSPP-based integrated devices and circuits show potential applications in various fields,[8−10] especially the high sensitivity to the surrounding circumstances makes LRSPP attractive for applications in controllable devices[11,12] and sensors.[13,14] Up to date, some research works have been reported on LRSPP-based attenuators, waveguides, and couplers,[7,14,15] as well as the controllable devices[12] which are more compactable than the conventional prism structure.[16] Furthermore, there have been some studies on embedding these LRSPP devices into traditional integrated devices, such as the LRSPP and dielectric hybrid coupler.[17]

We have proposed a novel refractive index sensor based on LRSPP[18] and analysed the range of refractive index difference Δn between the substrate and superstrate in which LRSPP can exist[18] theoretically. In this Letter, we report the fabrication and measurement on an LRSPP waveguide in a symmetric structure which consists of a metal stripe embedded in a homogeneous polymer BCB. The LRSPP is excited successfully by TM-mode light. The output field distribution versus the vertical and horizontal direction is measured. Meanwhile, the intrinsic propagation loss as low as 2 dB/mm is obtained by measuring the output peak power with different lengths. The experimental results show that we have realized the metal stripe waveguide of LRSPP with relative low loss.

Figure 1 shows the structure of the LRSPP waveguide. The fabrication processes are as follows: First, a 10-μm-thick layer of BCB (Cyclotene 3022-57, DOW Chemical Company) was spun and solidified on a silicon substrate wafer. After a layer of BP-212 photoresist was spun on the BCB layer, the stripe pattern was formed by photolithography. Then a 15 nm gold film was sputtered on a photoresist layer with carefully technical controlling. A photoresist remover was used to remove the photoresist pattern and the gold film sticking on it, which is named the lift-off process, therefore the gold stripe was formed. Finally, another 10-μm-thick layer of BCB was spun and solidified as the cover. The width of the gold stripe was changed to be 5 μm, 8 μm and 10 μm to see which one can have the LR-SPP field matching well with the single mode fibre, because the excitation efficiency from light to the LRSPP depends on the overlap integral between the input light and the field of LRSPP.

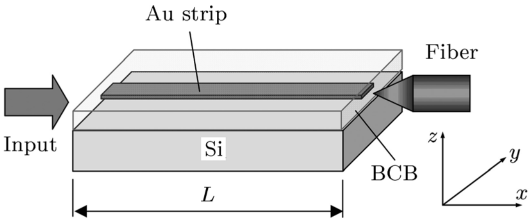

Fig. 1. A general view of sample's structure and the measurement method. The input fibre is fixed at the centre of the gold strip and the output fibre is scanning along the Y direction.

Figure 2 presents the AFM picture of the gold stripe with the width of 5 μm. The evaluation results

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* Supported by the National Basic Research Programme of China under Grant No 2007CB307004.

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show that the thickness is about 15 nm. Within the region of 1 μm×1 μm, the roughness of the gold film surface is less than 0.5 nm.

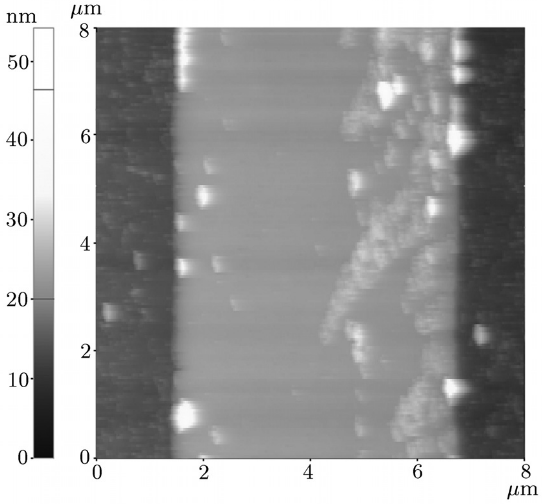

Fig. 2. AFM image for the fabricated Au stripe in width 5 mm. The brighter region is gold strip, and the darker region is the BCB polymer.

The measurement system for LRSPP excitation and propagation includes a light source, a polarization controller, an input tapered lens fibre, a precise fibre alignment system, an output tapered lens fibre, a power meter, and a monitor. The light source is a tunable LD source with the wavelength of 100 nm (1530–1630 nm). A polarization controller was used to control the polarization mode in order to ensure that the mode coupled into SPP mode is TM mode, because only TM mode could excite the SPP mode.[3] Tapered lens fibre was used to improve the coupling efficiency and to decrease the influence of noises. The precise fibre alignment system can be controlled by a computer via the GPIB card and the accuracy of this system is about 5 nm. The output port of the sample is coupled into the other tapered lens fibre and measured by the power meter.

The so-called end-fire method,[6] which means input a light field from one end of the gold waveguide by the fibre, was used here to excite the LR-SPP mode. An evident SPP mode was observed in the gold strip with 8 μm width, while the excitation efficiency was low for the samples in widths of 5 μm and 10 μm. By fixing the input fibre to the centre of the SPP waveguide and scanning the output fibre in the Y direction, we obtained the near field pattern of the LRSPP after transmission. Here we measured five samples with the same waveguide length of 2 mm. Figure 3 shows the output light field changed in the Y- and Z-directions, measured with the 8-μm-wide gold stripe. Light power with TM polarization was detected at the output facet of the gold stripe for all of the five samples. This means that the TM mode input light from the input fibre transfers into the LRSPP mode by end-fire excitation, and the LRSPP mode transfers into light again at the output facet after 2 mm transmission. The peak power of the output light is at the centre of the gold strip, i.e. at 0 μm, in Fig. 3, and the FWHM of the output light in the Y direction is about 13 μm which is compliant of the simulation results.[16] We also calculate the field distribution by the FEMLAB software and the results are shown in Fig. 3 (solid line). It is can be seen that the experiment spots in the Y direction are consistent with the simulation curve very well, while the output light power of negative part in the Z direction is higher than the simulation results. This is because the sub-layer BCB is not thick enough to avoid the field leaking to the Si substrate. The difference in the output power for the measured samples was caused by the difference of their facets, which can influence the LRSPP exciting efficiency.

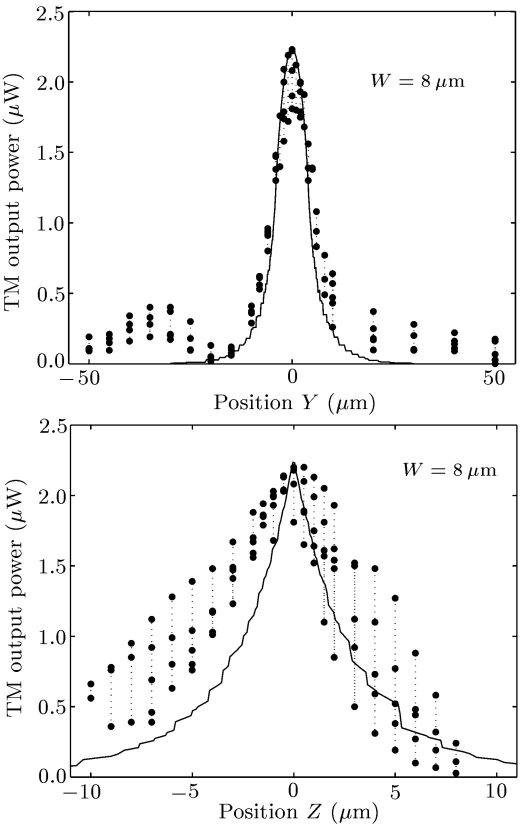

Fig. 3. TM-mode power measurement from the output facet of the 8-μm-wide gold strip after 2 mm LRSPP transmission, by scanning the output fibre. (a) Scanning along the Y direction. (b) Scanning along the Z direction. The dots are the experimental data measured from four samples. The solid line is the simulation results of TM-mode.

The same measurement was carried out for the LR-SPP waveguide with the strip length $L = 3$ mm, 4 mm, 5 mm. Five samples with the same gold strip width of 8 μm were measured for each length and the averages are shown in Fig. 4. It can be seen that the output power of the LRSPP decreases when the strip length increases, and the averages for each length fit to the Gauss function very well.

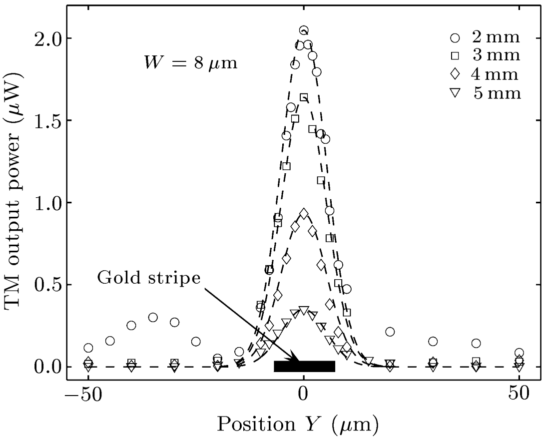

Fig. 4. Average output power of TM-mode for the 8-μm-wide gold stripe samples with different lengths from 2 mm to 5 mm.

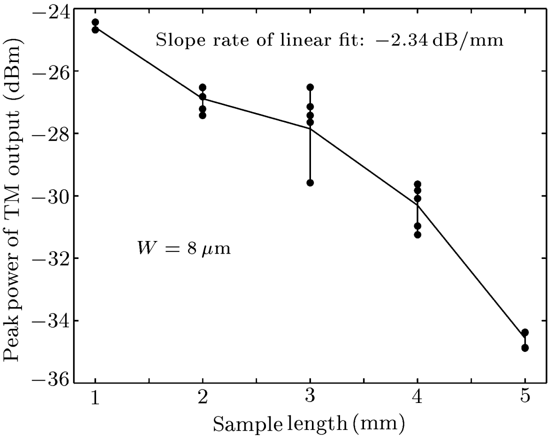

Fig. 5. Propagation loss of the 8-μm-wide gold stripe estimated from the peak power plotted in Fig. 4 (about 2.34 dB/mm). The black dots are the experimental data for different samples, and the solid line is the average value.

Figure 5 shows the propagation loss estimated from Fig. 4. When the sample length changes from 1 mm to 5 mm, and the output power of the LRSPP changes from −24.5 dBm to −34.5 dBm, therefore we can obtain the propagation loss of 2.34 dB/mm by fitting linearly. Here the input power is −4.5 dBm. We calculate the propagation loss of LRSPP with the FEMLAB software. The simulation propagation loss in the 8-mm-wide 15-nm-thick gold stripe is lower than 0.5 dB/mm, as the same as the result reported in Ref. [19]. It can be considered that the roughness of top-surface and side edge of the gold strip cause higher propagation loss measured from the samples. In addition, when the thickness and width of the gold strip reduce, the propagation loss would decrease while the excitation efficiency would also decrease.[19] Therefore, there is trade-off between the propagation loss and excitation efficiency.

In conclusion, we have realized an LRSPP waveguide successfully by fabricating a gold stripe embedded in a homogeneous polymer BCB. The LR-SPP is excited by TM-mode input light using an end-fire method. The intrinsic propagation loss as low as 2.34 dB/mm is estimated by measuring the output peak power of samples with different lengths. The realization of the LRSPP waveguide is very significant for development of LRSPP based devices.

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