Analysis of Plasmonic Mach-Zehnder Modulator with Metal Taper Structure Embedded in FTC-EO Polymer

○Naoya Hojo[1], Tomohiro Amemiya[2], Zhichen Gu[1],Nobuhiko Nishiyama[1], and Shigehisa Arai[1.2]
Dept. of Electrical and Electronic Engineering [1], QNERC [2], Tokyo Institute of Technology
E-mail: hojo.n.aa@m.titech.ac.jp

Abstract

We analyzed a Mach-Zehnder plasmonic modulator with metal-insulator-metal structure embedded by the Furan-Thiophene Chromophore. π-phase shift between two Mach-Zehnder arms can be obtained with a device length of 6.5 μm and the figure of merit of 3.1.

I. INTRODUCTION

Surface plasmon polaritons (SPPs), which allow strong light confinement beyond the fundamental diffraction limit, provide downsizing of conventional waveguide-based optical modulators [1-3]. Recently, several integrated plasmonic modulators have been reported [1, 2, 4]. However, the figure of merit (FoM) as a ratio of the extinction ratio to the transmission loss still leaves much to be improved (< 1).

In this paper, we estimate the theoretical possibility of plasmonic Mach-Zehnder (MZ) modulators on Silicon-on insulator (SOI) using the furan-thiophene chromophore (FTC) polymer with additional donor units, which has high electro-optic (EO) coefficient[5]. A double tapered structure is also introduced for light coupling between the modulator and Si waveguides. π-phase shift between two MZ arms can be obtained with a device length of 6.5 μm and the FoM is calculated to be 3.1. This value is far superior to that of other Si-based plasmonic modulators.

II. PROPERTIES OF MZ ARM REGION

The proposed plasmonic modulator is shown in Fig. 1. The device consists of a MZ waveguide on a SOI substrate with a metal slot embedded by the FTC polymer. Light is introduced into the device from a Si waveguide. The conversion into SPPs is initiated by tapering down a silicon waveguide and transferring the plasmonic modes onto a metallic 1×2 splitter.

In this structure, the gap-surface-plasmon-polariton waves are excited in the metal slot (inset of Fig. 2(a)). This produces strong optical confinement into the FTC polymer which has enhanced nonlinear optical property with large molecular hyperpolarizability [5]. Here a phase shift of ± π/2 rad in both two MZ arms can be obtained by applying a voltage signal to the metal-island (push-pull operation).

First of all, we calculated the MZ arm length and propagation loss for achieving π/2-phase shift by using finite element method. In simulation, we changed slot width W from 50 to 200 nm. Refractive indices of Si, SiO_2 and FTC polymer were set to be 3.45, 1.45 and 1.529, respectively. An EO coefficient of the FTC polymer was set to be 75 pm/V. Metal thickness h was fixed to be 220 nm, which is the same value as that of Si input waveguide.

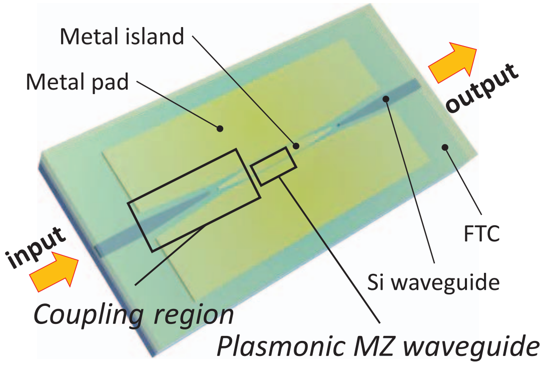

Fig. 1. Si-based Plasmonic Phase Modulator using furan-thiophene chromophore

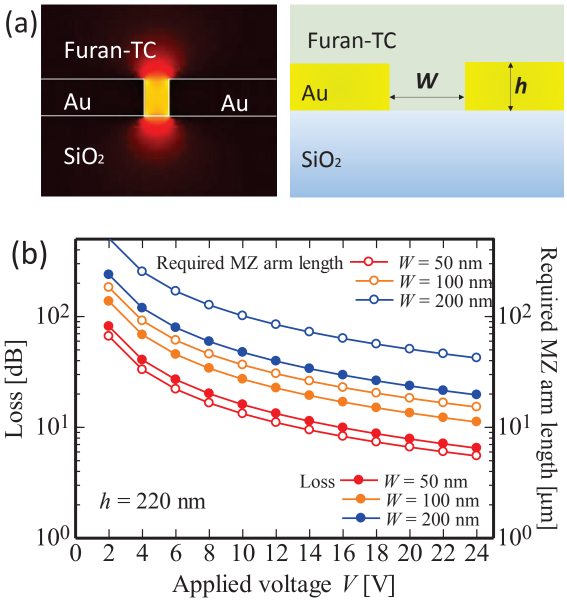

Fig. 2. (a) Mode field in metal slot waveguide. (b) Required MZ arm length to obtain π/2-phase shift and intrinsic propagation loss as a function of applied voltage.

Figure 2(b) shows the results for light of 1.55 μm wavelength, with slot width W as a parameter. Since the EO effect of FTC polymer increased with an applied voltage, the required MZ arm length to obtain π/2-phase shift can be shortened. This leads to a reduction of the intrinsic propagation loss of the MZ arm. If we set the slot width W to be 50 nm, π-phase shift between two MZ arms can be achieved with a device length of 6.5 μm for voltage swing from 0 to 20 V.

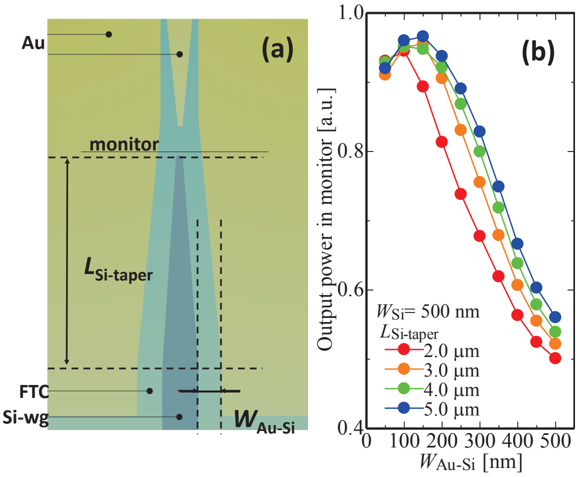

Fig. 3. Calculated conversion efficiency into SPPs initiated by tapering down a silicon waveguide, with the gap width $W_{Au\text{-}Si}$ and the Si taper length $L_{Si\text{-}taper}$ as parameters.

III. COUPLING LOSS BETWEEN INPUT SI WAVEGUIDE AND PLASMONIC MZ WAVEGUIDE

We carried out to simulate total insertion loss of the device considering coupling efficiency between the input Si waveguide and the plasmonic MZ waveguide by using finite-difference time-domain method. On the basis of the simulation results in Section II, the slot width W was fixed to be 50 nm.

First, we calculated conversion efficiency into SPPs initiated by tapering down a silicon waveguide (see Fig. 3(a)). In simulation, important dimension parameters are the gap width $W_{Au\text{-}Si}$ between the Si waveguide and the metal, and the Si taper length $L_{Si\text{-}taper}$. Figure 3(b) shows the results measured by a power monitor placed at the tip of the taper. With decrease of the gap width $W_{Au\text{-}Si}$, the distribution profile of the light becomes to be drawn toward both sides of the metal, which leads to an efficient conversion into SPPs. From this result, appropriate values of $W_{Au\text{-}Si}$ and $L_{Si\text{-}taper}$ were obtained to be 150 nm and 5.0 µm, respectively.

Using these parameters, we finally calculated the coupling loss between the input Si waveguide and the plasmonic MZ waveguide, with the metal taper length $L_{Au\text{-}taper}$ and the separation length L_{sep} as parameters (see Fig. 4a). As a result, minimum coupling loss of 3.3dB could be achieved when $L_{Au\text{-}taper}$ and L_{sep} were set to be 2.0 µm and 200 nm, respectively. Figure 5 shows an example of mode field distribution in the designed plasmonic phase modulator. We can see that appropriate π-phase shift between two MZ arms can be achieved with an applied voltage.

The above has led to the conclusion that a total insertion loss of the device is 12.8dB, and the figure of merit, which is defined as a ratio of extinction ratio to transmission loss, of the whole modulator is 3.1. These values are superior to those of other Si-based plasmonic modulators [1, 2, 4].

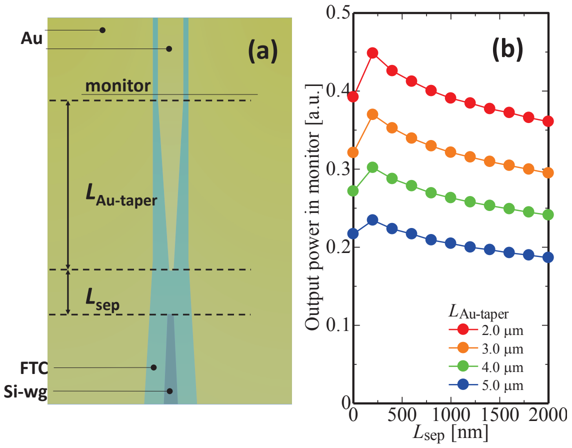

Fig. 4. Calculated coupling loss between the input Si waveguide and the plasmonic MZ waveguide, with the separation length L_{sep} and the Au taper length $L_{Au\text{-}taper}$ as parameters.

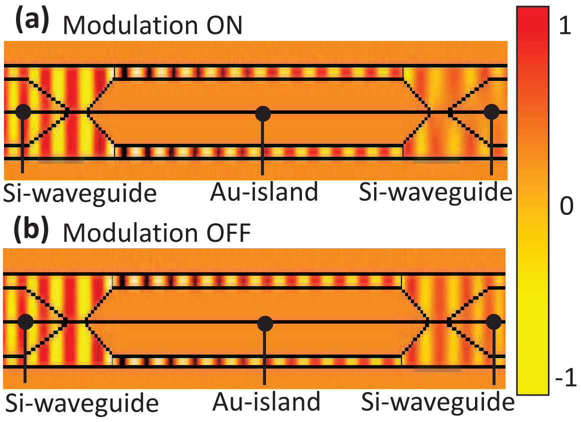

Fig. 5. Mode field distribution in the plasmonic MZ waveguide embedded by the FTC. (a) ON-state mode field distribution. A voltage of +/- Vπ/2 is applied on the Au island. (b) OFF-state mode field distribution.

ACKNOWLEDGMENT

This research was supported by JSPS KAKENHI Grant Numbers 24246061, 25709026, and 25420321. The authors would like to appreciate Drs. Akira Otomo, Toshiki Yamada and Chiyumi Yamada of NICT for their discussion

REFERENCES

[1] J. T. Guske, J. Brown, A Welsh, and Stefan, “Infrared surface plasmon resonance of AZO-Ag-AZO sandwich thin films,” *Opt. Express*, vol. 20, pp. 23215-23226, Aug. 2012.

[2] V. E. Babicheva, N. Kinsey, G. V. Naik, M. Ferrera, A. V. Lavrinenko, V.M. Shalaev, and A. Boltasseva, “Towards CMOS-compatible nanophotonics: Ultra-compact modulators using alternative plasmonic materials,” *Opt. Express*, vol. 21, pp. 27326-27337, Nov. 2013.

[3] T. Amemiya, E. Murai, Z. Gu, N. Nishiyama, and S. Arai, “GaInAsP/InP-based optical modulator consisting of gap-surface-plasmon-polariton waveguide: theoretical analysis,” *J. Opt. Soc. America. B*, vol. 31, pp. 2908-2913, Nov. 2014.

[4] C. Haffner, W. Heni, Y. Fedoryshyn, D. L. Elder, A. Melikyan, B. Baeuerle, J. Niegemann, A. Emboras, A. Josten, F. Ducry, M. Kohl, L.R. Dalton, D. Hillerkuss, C. Hafner, and J. Leuthold, “High-Speed Plasmonic Mach-Zehnder Modulator in a Waveguide,” *Proc. ECOC, PD.* 2.6, 2014.

[5] X. Zhang, I. Aoki, X. Piao, S. Inoue, H. Tazawa, S, Yokoyama, and A. Otomo, “Effect of modified donor units on molecular hyperpolarizability of thienyl-vinylene nonlinear optical chromophores,” *Tetrahedron Lett*, vol. 51, pp. 5873-5876, Nov. 2010.