Integrated Optical Polarizer for Silicon-on-Insulator Waveguides Using Evanescent Wave Coupling to Gap Plasmon–Polaritons

Ivan Avrutsky

Abstract—Resonant coupling to a gap plasmon–polariton supported by a metal–dielectric nanoscale multilayer on top of a silicon guiding core is proposed for polarization control in silicon-on-insulator waveguides. The device functionality relies on the unusual dispersion properties of the gap plasmon–polaritons, whose modal index can be significantly higher than the refractive index of the gap layer.

Index Terms—Photonic integrated circuits, plasmonics, polarizers, silicon-on-insulator.

I. INTRODUCTION

FUTURE development of integrated optics is expected to rely on utilization of well-established complementary metal-oxide-semiconductor (CMOS) fabrication technologies that have been proven to facilitate high-volume manufacturing of highly integrated electronic devices and systems. Silicon-on-insulator (SOI) platform has been introduced in microelectronics primarily in order to reduce parasitic electrical coupling through the substrate. It has been recognized soon that a thin slab of silicon on top of a transparent dielectric substrate or on top of a dielectric buffer layer forms a perfect optical waveguide. Defined by the bandgap energy of about 1.1 eV, the fundamental absorption in silicon starts at wavelength $\lambda < 1.12 \mu m$ so that silicon is highly transparent in the near-infrared spectral range. Monocrystalline defect-free SOI also shows negligible light scattering in the bulk of the silicon slab. The interfaces of the silicon slab are almost atomically flat so that light scattering at the imperfections of the waveguide interfaces—the major source of losses in planar waveguides—is practically eliminated. The refractive index contrast in the Si/SiO$_2$ material system is unusually high: $n(Si) \approx 3.48$, $n(SiO_2) \approx 1.44$. This allows for very strong confinement of guided modes, and ultimately, for a very high degree of integration that is hardly achievable using traditional integrated optical material systems. SOI-based integrated optics quickly evolved into a separate research field—silicon photonics [1]–[3]. At the telecom wavelengths, many silicon photonic devices have been successfully demonstrated. Examples include optical multiplexers/demultiplexers based on arrayed waveguide gratings, silicon chip Raman lasers, photonic circuits based on photonic crystals, and others.

Even higher degree of integration of optical devices is expected using light confinement in metal–dielectric nanostructures supporting plasmonic modes [4]–[7]. Combining silicon photonics and plasmonics is believed to provide the highest degree of integration for optical devices.

Polarization control is an essential component of integrated optical systems. When achieving polarization-independent operation of a device is difficult, the undesirable polarization must be completely blocked to ensure proper functionality of the device. For example, in multiplexers/demultiplexers for dense wavelength division multiplexing applications, even a minor difference between the propagation constants of guided modes with different polarizations may result in substantial crosstalk. Several schemes have been proposed for integrated optical polarizers implemented in SOI. The lateral Bragg reflector structure made of Si/Si$_3$N$_4$ has been shown to be polarization-sensitive, especially when light approaches Si/Si$_3$N$_4$ interfaces at the Brewster angle [8]. In such a structure, also known as antireflection reflecting optical waveguide, light is confined to a low-index core. The lateral confinement requires several Bragg periods, and thus it can never be really strong. The vertical antireflection reflecting optical waveguide structure is also polarization-sensitive [9], and it also provides weak light confinement to a low-index core. The scheme employing 3-dB multimode interference couplers and Mach–Zehnder interferometer with rib waveguides of different widths [10] relies on birefringence in the rib waveguides. It works in a spectral range of about 45 nm. The Mach–Zehnder interferometer with multimode interference couplers altogether has a relatively large footprint. The scheme that uses vertically coupled microring resonator [11] is expected to provide 20-dB polarization splitting ratio, however, in a very narrow range of wavelength. It must be stressed that the devices described in [8]–[11] are polarization splitters rather than polarizers. As a polarization splitter provides additional functionality compared to a polarizer, it justifies a larger footprint and a more complex internal structure.

In the simplest integrated optical polarizer, transverse magnetic (TM) polarized light is coupled to a surface plasmon–polariton mode, which then quickly decays due to losses in the metal. Transverse electric (TE) mode in a system made of isotropic materials cannot be coupled to the plasmon–polariton, and thus propagates with much smaller losses. These polarizers are known since 1970s [12]. It worth mentioning that some polarization discrimination is known to exist in waveguides with metallic claddings even if there is no coupling to plasmon–polaritons: due to different penetration of light into the metallic...
cladding, losses for TE-polarized mode are lower compared to losses for TM-polarized mode. So, the simplest structure of an integrated optical polarizer would contain just a metallic coating over the dielectric core guiding layer [13]–[15]. By introducing an appropriately designed dielectric cladding layer between the guiding layer and the metal, efficient interaction is facilitated between the mode confined to the guiding layer and the plasmon–polariton at the metal/cladding layer interface, leading to dramatic improvement of the polarizer performance.

Unfortunately, such an approach cannot be directly applied to the SOI waveguides because it is difficult to match the propagation constant of a guided mode in an SOI waveguide to that of a surface plasmon–polariton mode. The problem is that the modal index of the mode guided by the silicon core is large (comparable to the refractive index of silicon), while the modal index of the plasmon–polariton is low, being just slightly above the refractive index of the dielectric cladding layer. On the other hand, metal–dielectric nanoscale multilayers have been shown to support high-index plasmonic modes. In a structure made of three pairs of silica (∼29 nm)/gold (∼25 nm) nanolayers, guided modes with indexes 2.31 and 2.88 have been experimentally verified [16]. The simplest high-index plasmonic mode is, of course, a gap plasmon–polariton supported by a thin dielectric layer sandwiched between metal layers.

In this paper, we propose an integrated optical polarizer for high-index-contrast SOI waveguides that operate through coupling of TM-polarized guided mode to a gap plasmon–polariton mode. Numerical illustration is provided for a planar waveguide while there are all expectations to believe that the proposed approach will work equally well for rib waveguides. In a nutshell, the proposed structure consists of several nanoscale metal–dielectric layers on top of an SOI waveguide. In a particular design example, a 120-µm-long section of such a loaded waveguide provides more than 30 dB attenuation to TM-polarized mode in the wavelength range as wide as 350 nm (from about 1315 nm to 1665 nm), while the insertion loss for the transverse electric (TE) mode is from 2 dB to 4 dB. To the best of our knowledge, no other integrated optical polarizer for SOI waveguides can operate in such a wide spectral range, and no other polarizer would have such a small footprint.

II. BASIC STRUCTURE AND DESIGN PRINCIPLES

The basic structure of the proposed integrated optical polarizer comprises an SOI waveguide and a metal–dielectric nanoscale multilayer supporting high-index plasmonic modes. In the simplest case, this can be a gap plasmon–polariton (GPP) confined to a dielectric gap layer between metallic claddings. More sophisticated structures would employ so-called bulk plasmon–polaritons (BPP) [16] supported by structures with multiple gap layers separated by thin metal layers. The gap layer thickness is adjusted to provide phase synchronism between the GPP mode (or one of the BPP modes) and TM-polarized guided mode of the SOI structure. Strong coupling is achieved by using a thin cladding layer separating the silicon guiding core from the metal–dielectric multilayer. Even though functioning of the device relies on resonant coupling, the strong coupling together

with rather high optical losses for GPP allows for the device operation in a wide spectral range. The same factors contribute to shrinking the footprint of the polarizer.

Cross section of the structure under analysis is shown in Fig. 1. Detailed description of the structure is as follows. The SOI waveguide contains a silicon carrier wafer, a silica buffer layer (subscript b in further formulas), and a silicon guiding layer (g). The buffer layer is typically thick enough so that the modal field of guided light waves does not reach the carrier wafer. A thin cladding layer (c) is placed on top of the guiding layer to separate the SOI waveguide from the structure supporting the gap plasmon–polariton, which is essentially a pair of metal layers (bottom metal, m1, and top metal, m2) with a dielectric gap layer (d) between them. The entire structure may be covered by the protection layer (p) to protect the top metal layer from mechanical damages in further wafer processing.

One of the attractive features of the polarizer structure considered here is that the overall design can be completed by adjusting the thicknesses of the layers only while their refractive indexes would be defined by the choice of CMOS-compatible materials. The guiding layer is obviously made of silicon. The buffer, cladding, gap, and protection layers all may be made of silica. A good material choice for both metal layers is gold. Optical properties of silicon, silica, and gold in the wavelength range of interest are summarized in Table I.

Approximate values of layer thicknesses can be found easily by comparing modal indexes of a TM-polarized mode in the SOI waveguide, nTM, and the GPP mode confined to the dielectric layer sandwiched between metal layers, nGPP. The modal index in a slab waveguide is found by solving numerically the dispersion equation

\[
\frac{2\pi}{\lambda} t_g \sqrt{n_g^2 - n_{TM}^2} = \text{atan} \left( \frac{n_g^2}{\sqrt{n_g^2 - n_{TM}^2}} \right) + \text{atan} \left( \frac{n_g^2}{\sqrt{n_g^2 - n_{TM}^2}} \right) + N\pi
\]

where \(\lambda\) is the vacuum wavelength of light, \(t_g\) is the thickness of the guiding layer, \(n_g, n_b\), and \(n_c\) are the refractive indexes of the guide, buffer, and cladding respectively, and \(N\) is the mode order \((N = 0\) for the fundamental mode). For the practically
TABLE I

<table>
<thead>
<tr>
<th>Material</th>
<th>Formula and wavelength range</th>
<th>Optical constants at $\lambda = 1500$ nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon$^a$</td>
<td>Sellmeier-like: $n(\lambda) = \sqrt{\frac{A}{\lambda^2} + \frac{B\lambda^2}{\lambda^2 - C^2}}$</td>
<td>$n = 3.4804$</td>
</tr>
<tr>
<td></td>
<td>$1.2 \mu m &lt; \lambda &lt; 14 \mu m$</td>
<td>$\varepsilon = 11.6858$, $\lambda_1 = 9.39816 \times 10^4 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$B = 8.10461 \times 10^3$, $\lambda_1 = 1107.1 \mu m$</td>
<td>$\varepsilon_m$</td>
</tr>
<tr>
<td>Silica$^a$</td>
<td>Sellmeier: $n(\lambda) = \sqrt{1 + \frac{A\lambda^2}{\lambda^2 - C^2}}$</td>
<td>$n = 1.4446$</td>
</tr>
<tr>
<td></td>
<td>$0.21 \mu m &lt; \lambda &lt; 3.71 \mu m$</td>
<td>$\varepsilon = 2.304976$, $\lambda_1 = 116.2414 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$\lambda_1 = 0.8974974$, $\lambda_2 = 9890.161 \mu m$</td>
<td>$\varepsilon_m$</td>
</tr>
<tr>
<td>Gold$^a$</td>
<td>Druke: $\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\delta)}$</td>
<td>$\Re(\varepsilon) = -117.3$</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon(\omega) = 3.836$</td>
<td>$\Im(\varepsilon) = 220 \text{ nm}$</td>
</tr>
<tr>
<td></td>
<td>$\delta = 2\pi \times 2.175 \times 10^{13} \times t^4$</td>
<td>$\frac{\partial \Re(\varepsilon)}{\partial \lambda} = -0.158 \text{ nm}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\omega_p = 2\pi \times 6.48 \times 10^{17} \times t^4$</td>
<td>$\frac{\partial \Im(\varepsilon)}{\partial \lambda} = 7.67 \times 10^{7} \text{ nm}^{-1}$</td>
</tr>
</tbody>
</table>


In the case of a very thin gap layer, the last equation can be approximately solved as follows:

$$n_{GPP} \approx \sqrt{n_d^2 + \frac{1}{2} \left( \frac{\lambda}{\pi t_d} \varepsilon_m \right)^2 + \left( \frac{\lambda}{\pi t_d} \varepsilon_m \right)^2 \left( \frac{\lambda}{\pi t_d} \varepsilon_m \right)^2 + \frac{1}{4} \left( \frac{\lambda}{\pi t_d} \varepsilon_m \right)^2 \left( \frac{\lambda}{\pi t_d} \varepsilon_m \right)^2}.$$  

(4)

From (4), in approximation $t_d \rightarrow 0$, the modal index of the gap plasmon–polariton, $n_{GPP}$, is scaled inversely proportional to the gap layer thickness. Due to this, even using low-index material such as silica, one can always find suitable thickness of the dielectric gap layer to match relatively high value of the modal index of the SOI waveguide found from (1) or (2).

Thickness of the bottom metal layer $t_{m1}$ should be small enough to let the guided mode in the gap layer tunnel to the cladding layer and thus to the SOI waveguide. Gold film would be semitransparent at thickness in the range of few dozens of nanometers. Thickness of the top metal layer $t_{m2}$ as well as that of the protection layer $t_p$ are not critical. Thickness of the cladding layer $t_c$ affects the coupling strength between the mode in SOI waveguide and the gap plasmon–polariton.

The simple consideration outlined earlier should be viewed as a qualitative justification that a proper thickness of the gap layer can always be found so that the modal index of the gap plasmon–polariton would match the index of the SOI waveguide. It can also be used for choosing reasonable initial values of layer thicknesses, which further should be optimized by a more careful numerical modeling of guided modes in the entire structure. One should note though, that in an optimized structure, the metal layers as well as the cladding layer between the silicon guiding core and the bottom metal layer are nanoscale thin rather than infinitely thick. For this reason, the optimal thicknesses of the layers may differ from the values predicted by formulas (2) and (3).

III. Sample Design

In this section, we present a sample design of an integrated optical polarizer operating in the wavelength range from about 1315 to 1665 nm. Thickness of the silicon guide layer is chosen to be $d_g = 220$ nm so that the SOI waveguide supports single mode in the wavelength range of interest. Thicknesses of both metal layers were set at $t_{m2} = t_{m1} = 30$ nm. Increasing the bottom metal layer thickness generally results in narrowing the working range of the polarizer, while decreasing this thickness eventually leads to rather high losses even for TE-polarized mode. The thickness of the protection layer was set to be $t_p = 100$ nm. This parameter is not crucial and does not require optimization. Thickness of the dielectric gap layer $t_d$ was adjusted so that the dispersion curves representing the modal indexes for TM-polarized modes in the entire structure would show clear anticrossing in the middle of the wavelength range of interest. The adjusted value of the dielectric gap layer thickness was $t_d = 30$ nm in this sample design. Thickness of the cladding was set at $t_c = 60$ nm.
Due to the coupling, the guided mode of the SOI waveguide and the gap plasmon–polariton mode are mixed forming the supermodes. Modal indexes of the supermodes as functions of wavelength have been calculated using the transform matrix method, and are shown in Fig. 2, top. To be specific, the supermode with higher modal index is labeled $A$, and the other one is labeled $B$. The smallest distance between the dispersion curves

$$\Delta n_{\text{min}} = \min(\Re(n_A(\lambda)) - \Re(n_B(\lambda)))$$

happens to be at $\lambda_{\text{min}} = 1440$ nm, and is equal to $\Delta n_{\text{min}} = 0.143$.

Imaginary part of the modal index defines propagation losses $\alpha$ according to

$$\alpha = \frac{4\pi}{\lambda} \Im(n(\lambda)).$$

Propagation losses for the supermodes $A$ and $B$ are shown in Fig. 2, bottom. At wavelengths far from the anticrossing, the supermodes turn into the modes confined to either the silicon core of the SOI waveguide or to the dielectric gap between the metal layers. In particular, the supermode $A$ at shorter wavelength becomes a mode in silicon core (low loss), and at longer wavelength it turns into the gap plasmon–polariton (high loss). The supermode $B$ behaves complementarily.

The supermodes’ modal indexes and propagation losses comprehensively define properties of guided modes in this structure. However, from a practical perspective, a different type of information on the structure would be important. Namely, assuming a section of length $L$ of the SOI waveguide is loaded with the structure described earlier, what are the attenuation factors for TE and TM modes supported by the SOI waveguide?

Following estimations are being simplified by avoiding discussion of reflections at the edges of the loaded section as well as mode coupling at the edges. To provide some justification for this simplification, let us say that the loaded section can be manufactured in such a way that the metal–dielectric structure would approach the SOI waveguide adiabatically. Anyway, the major effect of having the metal–dielectric multilayer in close proximity to the silicon waveguide consists in polarization-dependent loss.

Estimation for attenuation factor of the TE mode is straightforward. The TE mode of the SOI waveguide would propagate as TE mode of the entire structure in the loaded section. Using the same transfer matrix method, we find $n_{\text{TE}}(\lambda)$, then find propagation losses according to (6), and finally express the attenuation factor in logarithmic scale

$$\Gamma = -10 \log(\exp(-\alpha L)) = 10 \log(e) \times \alpha L.$$  \hspace{1cm} (7)

In the logarithmic scale, the attenuation is directly proportional to propagation losses, which make it easier to draw preliminary conclusions about the polarizer performance using the graphs for the propagation loss as a function of wavelength.

In the case of TM-mode, estimation of the attenuation factor is somewhat convoluted because one needs to know the contribution of losses of both supermodes $A$ and $B$ to the losses of TM-polarized mode in the SOI waveguide. Following consideration allows for simple estimations. The coupled mode theory [17] allows for estimating the coupling strength $\kappa$ from the minimal difference between the modal indexes (5)

$$\kappa = \frac{\pi}{\lambda_{\text{min}} \Delta n_{\text{min}}}.$$  \hspace{1cm} (8)

In this sample design, the coupling strength is about $\kappa = 3123$ cm$^{-1}$. It means that at exact resonance, at wavelength $\lambda = \lambda_{\text{min}}$, the optical power is being completely transferred from one waveguide to another while propagating the distance equal to the coupling length

$$L_c = \frac{\pi}{2\kappa} = \frac{\lambda_{\text{min}}}{2\Delta n_{\text{min}}}$$  \hspace{1cm} (9)

that is as short as 5.035 $\mu$m. That is, every $2L_c \approx 10.07 \mu$m marks a complete period in transferring optical power back and forth between the coupled waveguides. Consequently, in exact resonance, when the loaded section is much longer than the period of the optical power transfer $L \gg 2L_c$, it is reasonable to assume that losses for the TM-mode would be about $\alpha_{\text{SOI+GPP}}$, where $\alpha_{\text{SOI}}$ and $\alpha_{\text{GPP}}$ are the optical losses in individual waveguides in the absence of coupling. Of course, the length of the loaded section is not necessarily an exact integer multiple of the optical power transfer period, but in assumption $L \gg 2L_c$, one can safely assume that the losses are averaged. Moreover, by taking into account that at the end of the loaded section a fraction of optical power may still reside in the plasmon–polariton mode, one concludes that the estimation based on averaging the losses would always produce a conservative result.

At wavelength other than the wavelength of exact resonance $\lambda \neq \lambda_{\text{min}}$, the coupled mode theory predicts that the energy transfer between the waveguides is not complete, but it still follows the periodical pattern with the period

$$2L_c' = \frac{\lambda}{(n_A(\lambda) - n_B(\lambda))} < 2L_c.$$  \hspace{1cm} (10)
even shorter than $2L_c$. This justifies appropriate averaging of losses even far from the resonance.

Within the coupled mode theory, once all optical power is initially confined to one of the waveguides (SOI waveguide in this case) during propagation in the coupled waveguide system, the fraction of the power transferred to the other waveguide (gap plasmon–polariton) oscillates harmonically between $f_{\text{GPP}}^{\text{max}} = 0$ and $f_{\text{GPP}}^{\text{min}} = \frac{f_{\text{SOI}}^{\text{max}}}{4k^2 + \Delta \beta^2}$, where

$$\Delta \beta = \frac{2\pi}{\lambda} \left( \text{Re}(n_{\text{GPP}}(\lambda)) - \text{Re}(n_{\text{SOI}}(\lambda)) \right)$$

is the detuning from the exact resonance, and $n_{\text{GPP}}(\lambda)$ and $n_{\text{SOI}}(\lambda)$ are the modal indexes of the gap plasmon–polariton mode and the mode supported by the SOI waveguide in the absence of coupling. Averaged over the large number of periods ($L \gg 2L_c$ and $L \gg 2L'$), the fraction of optical power carried by the GPP mode becomes

$$f_{\text{GPP}} = \frac{2k^2}{4k^2 + \Delta \beta^2}.$$  

Similarly, the fraction of optical power left in the SOI waveguide oscillates harmonically between $f_{\text{SOI}}^{\text{max}} = 1$ and $f_{\text{SOI}}^{\text{min}} = \frac{\Delta \beta^2}{4k^2 + \Delta \beta^2}$. After averaging over the large number of periods, the fraction of power carried by the SOI waveguide is estimated to be

$$f_{\text{SOI}} = \frac{2k^2 + \Delta \beta^2}{4k^2 + \Delta \beta^2}.$$  

Average losses seen by the TM-polarized mode initially confined to the SOI waveguide become

$$\alpha_{\text{TM}} = f_{\text{SOI}} \alpha_{\text{SOI}} + f_{\text{GPP}} \alpha_{\text{GPP}}.$$  

In order to complete calculation of losses, one needs to know the detuning $\Delta \beta$ and losses for the SOI waveguides $\alpha_{\text{SOI}}$ and for the gap plasmon–polariton $\alpha_{\text{GPP}}$ in the absence of coupling. When the coupling is weak, the modal indexes $n_{\text{GPP}}$ and $n_{\text{SOI}}$ and then the optical losses $\alpha_{\text{GPP}}$ and $\alpha_{\text{SOI}}$ in individual waveguides can easily be calculated by splitting the entire structure into two disconnected subsystems. With a strong coupling like in this case, it is better to evaluate properties of individual waveguides using data on the supermodes. In particular, a reasonable estimation can be made by taking the losses values far from the resonance and then using linear approximation for the entire wavelength interval.

Using data from Fig. 2, at a wavelength of $\lambda_1 = 1200$ nm, losses for the SOI and GPP modes were calculated to be $\alpha_{\text{SOI}}(\lambda_1) = 160$ cm$^{-1}$ and $\alpha_{\text{GPP}}(\lambda_1) = 1525$ cm$^{-1}$. At a wavelength of $\lambda_2 = 1800$ nm, the corresponding values were found to be $\alpha_{\text{SOI}}(\lambda_2) = 177$ cm$^{-1}$ and $\alpha_{\text{GPP}}(\lambda_2) = 1462$ cm$^{-1}$. Between the wavelengths of 1200 and 1800 nm, the values for $\alpha_{\text{GPP}}(\lambda)$ and $\alpha_{\text{SOI}}(\lambda)$ are interpolated linearly

$$\alpha_{\text{SOI}}(\lambda) = \frac{\alpha_{\text{SOI}}(\lambda_1) \times (\lambda_2 - \lambda) + \alpha_{\text{SOI}}(\lambda_2) \times (\lambda - \lambda_1)}{\lambda_2 - \lambda_1}$$

$$\alpha_{\text{GPP}}(\lambda) = \frac{\alpha_{\text{GPP}}(\lambda_1) \times (\lambda_2 - \lambda) + \alpha_{\text{GPP}}(\lambda_2) \times (\lambda - \lambda_1)}{\lambda_2 - \lambda_1}.$$  

The detuning $\Delta \beta$ can also be evaluated from the data on the supermodes. Indeed, in the coupled mode theory, the anticrossing of dispersion curves for the supermodes is described by

$$\beta_{A,B} = \frac{\beta_{\text{SOI}} + \beta_{\text{GPP}}}{2} + \sqrt{\kappa^2 + \left(\frac{2\Delta \beta}{2}\right)^2}$$

where $\beta$ is the propagation constant and the subscripts $A$, $B$, SOI, and GPP are used as defined earlier. One can find from (17) that

$$\Delta \beta = \pm \sqrt{\frac{4\pi^2}{\lambda^2} \left(\text{Re}(n_A) - \text{Re}(n_B)\right)^2 - \kappa^2}$$

where the sign “+” is used for $\lambda < \lambda_{\text{min}}$ and “−” for $\lambda > \lambda_{\text{min}}$.

With the coupling strength $\kappa$ found according to (8) and (5), (18) defines the detuning $\Delta \beta$, and then the factors $f_{\text{GPP}}$ (12) and $f_{\text{SOI}}$ (13) relying exclusively on dispersion curves for the supermodes $n_A(\lambda)$ and $n_B(\lambda)$.

The detuning found from (18) allows for calculating the fractions (12) and (13), and then, substituting (15) and (16) into (14) gives the losses for the TM-polarized mode.

The simulation results are presented in Fig. 3. With the loaded section $L = 120$ $\mu$m long, attenuation as large as 30 dB is found in the 350-nm-wide range from approximately 1315 to 1665 nm. At the same time, attenuation for the TE-polarized mode is between 2 and 4 dB across the wavelength range of interest.

Let us note that the modal attenuation estimated as described earlier is essentially based on calculating total power in both TM-polarized modes: the one confined to the SOI and the one supported by the metal–dielectric multilayer. Due to periodical optical power transfer between these modes, the actual attenuation seen by the SOI mode may appear to be even larger at some wavelengths. So, the attenuation data for the TM-mode presented in Fig. 3 are conservative.

For illustration purposes, we also present the field distributions across the structure for TE- and TM-polarized modes at

![Graph](image-url)
wavelengths 1200, 1440, and 1800 nm (Fig. 4), calculated using the transform matrix method.

Shown in Fig. 4 is the tangential component of the electric field for the TE-polarized mode and the tangential component of the magnetic field for the TM-polarized mode.

The graph illustrates how the supermodes gradually transform into modes of individual waveguides as the detuning from exact resonance increases in one direction (to shorter wavelengths) or another (to longer wavelengths). These fields’ distributions have not been used in the evaluation of losses: the dispersion curves shown in Fig. 2 provide complete information on modal losses in the system.

IV. CONCLUSION

In conclusion, we propose an integrated optical polarizer that employs resonant coupling of TM-polarized mode in SOI waveguide to a high-index mode supported by a nanoscale metal–dielectric multilayer, such as the gap plasmon–polariton. Analytical estimation shows that with sufficiently small thickness of the dielectric gap layer between the metal claddings, resonance between the guided mode carried by the SOI structure and the gap plasmon–polariton mode can always be achieved. Supermodes in a sample structure are analyzed using the transfer matrix method. Attenuation for the TM-polarized mode initially coupled to the SOI waveguide is estimated using the coupled mode theory.

REFERENCES


Ivan Avrutsky was born in Ukraine, in 1963. He received the M.Sc. degree in physics with specialization in laser physics and Honorary Red Diploma from Moscow Institute of Physics and Technology, Moscow, Russia, in 1986, and the Ph.D. degree in physics and mathematics with specialization in quantum electronics from the General Physics Institute of Russian Academy of Sciences, Moscow, in 1988.

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