Theoretical Analysis of On-Chip Vertical Hybrid Plasmonic Nanograting

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Abstract
A complementary metal oxide semiconductor (CMOS) compatible photonic-plasmonic waveguide with nanoscale dimensions and better optical confinement has been proposed for the infrared (IR)–band applications. The design is based on the multi-layer hybrid plasmonic waveguide (Si–SiO₂–Au) structure. The 3D-finite element method (FEM)–based numerical simulations of single slot hybrid plasmonic waveguide (HPWG) confirms 2.5 dB/cm propagation loss and 15 μm⁻² confined intensity. Moreover, its application as dual-slot nanograting is studied with higher propagation length and ultra–low–dispersion near the 1550–nm wavelength. The proposed low-dispersion nanoscale grating design is suitable for future lab–on–chip nanophotonic integrated circuits.

Keywords Nanograting · Hybrid plasmonic waveguide · Surface plasmon · Finite element method · Dispersion

Introduction
Nowadays, CMOS technology makes it possible to realize the ultrafast transistor with a feature size less than 20 nm. The on-chip integration of optoelectronic components follows the well-known Moore’s law, and the demand for smaller feature sizes is increasing day by day. The nanoscale devices with smaller dimensions result in low power consumption and fast speed of operation with minimum delay. This delay limits the data handling capacity of the optoelectronic chips. Hence, optical interconnect with higher bandwidth, lower delay, and minimum power requirement are favored for optical transmission of the user data.

Silicon photonics technology is a better solution to reduce the feature size of optical transistors, where the same silicon (Si) layer is used to fabricate various silicon transistors. This technology also overcomes the problem of diffraction limit faced by the fiber optics-based optical components [1]. To date, many plasmonic waveguide designs have been reported. Generally, plasmonic waveguides (metal-dielectric) suffer from ohmic losses (due to metal layer), optical confinement, and higher dispersion, as discussed in ref [2–4]. To overcome these problems, a multi-layer hybrid plasmonic waveguide (HPWG) design is proposed in this work. In contrast to the conventional plasmonic waveguide, the HPWG waveguide supports better mode confinement and lower propagation losses.

In this paper, Si–SiO₂–Au-based plasmonic waveguide and nanograting are presented with better mode area, improved confinement intensity, low dispersion, and enhanced propagation length. The optical transmission losses are reduced because quasi-TM mode (fundamental mode) is confined between the higher-index silicon (Si) layer and lower-index silicon dioxide (SiO₂) slot. The work has been organized as follows: sect. “Simulation Details” discusses the device and simulation details. Section “Hybrid Plasmonic Nanograting” focuses on the modeling of HPWG nanograting as per the Bragg grating theory. In the last, conclusions are made in sect. “Conclusion.”

Simulation Details
Figure 1a shows the cross-sectional view of the proposed HPWG with Si–SiO₂–Au-based multi-layer structure. Gold (Au) is used as a metal layer with 100-nm thickness (hAu) and placed over the silicon dioxide substrate. The dependence of the imaginary part of permittivity on the photon energy for Au is plotted in Fig. 1b [1].
permittivity is defined as per the Drude model [5]. The refractive index for the silicon dioxide as slot and substrate is taken as per the dispersion relation [6]. The proposed waveguide is simulated using radio-frequency (RF) module of COMSOL multi-physics software [7]. The device is discretized using 1,285,045 triangular meshes. For optical waveguide modeling, mesh-type and geometric division are significant steps in the device modeling. We have used an element size of 0.255 nm for the Au metal layer. Furthermore, slot waveguide height (\(h_{\text{slot}}\)) and width (\(W_{\text{slot}}\)) are fixed to 100 nm and 350 nm, respectively. The lower-index slot region supports highly confined quasi-TM mode with silicon as a high-index layer and gold (Au) as metal layer (see Fig. 2a). Also, the proposed HPWG waveguide dispersion relation is solved numerically with COMSOL simulations, following ref [7]. Figure 2b shows the variation of propagation constant (\(\beta = n_{\text{eff}}/\lambda_0\)) versus frequency. The cutoff frequency is nearly 110 THz; see Fig. 2b.

Further, the RF module is used to perform the optimized study of normalized effective mode area \((A_{\text{eff}}/A_0)\), and propagation length \((L_p)\), follow Fig. 2c. Here, \(A_0\) is the diffraction-limited mode area in free space, i.e., \(\lambda_0^2/4\). These parameters are derived using conventional waveguide theory. Here, \(A_{\text{eff}}\), the effective mode area is defined as the ratio of total mode energy and peak energy density and formulated as [1],

\[
A_{\text{eff}} = \frac{1}{\text{Max}\{W(r)\}} \int W(r) dA
\]

where the energy density \(W(r)\) is defined as [1],

\[
W(r) = \frac{1}{2} \text{Re} \left\{ \frac{d\omega e(r)}{d\omega} \right\}] |E(r)|^2 + \frac{1}{2} \mu_0 |H(r)|^2
\]

\(E(r)\) and \(H(r)\) are the electric and magnetic fields, respectively; \(\varepsilon(r)\) is the electric permittivity; and \(\mu_0\) is the vacuum permeability or magnetic constant. Also, the propagation length (L) of the bound modes is calculated using the below relation [1]:

\[
L_p = \frac{1}{2 \text{Im} (\beta)}
\]

According to Fig. 2c, the normalized effective mode area and propagation length of suggested HPWG with \(h_{\text{slot}} = 25\) nm (solid line) are 0.05 and 60 \(\mu\)m, respectively. The slot with a smaller height, such as \(h_{\text{slot}} = 5\) nm, shows a lesser mode area (highly confined modes). The finite element method–based numerical simulations confirm that most of the electromagnetic energy is confined (localized) within the slot region of the suggested single slot HPWG; see Figs. 2a and 3a. Figure 3b shows that, as the width is increased from 250 to 400 nm, the waveguide suffers low losses. The 3D COMSOL simulations confirm propagation loss of 2.5 dB/cm and confined intensity of 15 \(\mu\)m, respectively.

**Hybrid Plasmonic Nanograting**

In this section, we have performed the modeling of on–chip HPWG nanograting with filtering wavelength or Bragg wavelength (\(\lambda_B\)) of 1549 nm. The regions I and II are like metal-dielectric-metal (MDM) type structure (see Fig. 4), whose effective refractive index is calculated as per ref. [8, 9]. For grating design, we solved the well-known Bragg grating relation [11, 12]. Various variables \((p, q, n_{\text{eff}1},\) and \(n_{\text{eff}2})\) satisfying Eq. 4 are summarized in Table 1.

\[
k_0 [n_{\text{eff}1} (p-q) + n_{\text{eff}2} q] = (2m-1)\pi
\]

Further, we excite the TM mode near the input port \(P_{\text{Input}}\). We observed that the highly confined hybrid plasmonic mode (quasi-TM mode) starts propagating through the low-index slot region (see inset of Fig. 4, symmetric and anti-symmetric modes). The cutoff frequency is calculated as per the dispersion plot (Fig. 5a). Also, Fig. 5b shows the frequency behavior of HPWG nanograting with/without gratings. For higher data rates, waveguide dispersion should be as low as possible to avoid the pulse broadening of the bound modes [10–12]. Hence, nanoscale optical
Gratings are required for a more extensive integration area in the modern photonics integrated circuits (PICs). For this, nanograting structure is proposed with periodic variation of refractive index across region I and region II (see Fig. 4). The presence of grating in the Si layer helps in controlling the bound modes effectively near 1550 nm. Also, the suggested grating structure shows lower insertion losses ~20% over the 1530- to 1560-nm wavelength window.

Fig. 2  

(a) The electric field (V/m) distribution near the output port P_{output} at \( \lambda = 1.55 \) μm.  

(b) The plot of propagation constant (\( \beta \)) vs frequency, and (c) mode area and propagation length vs width (w) with different slot heights.

Fig. 3  

(a) The electric field line plot of the proposed Si–SiO2–Au-based HPWG waveguide, and (b) waveguide loss and confined intensity versus width (w).
A low-dispersion nanoscale Bragg grating is numerically characterized using finite element method (FEM)–based 3D-COMSOL multi-physics simulator [7]. To study its transmission characteristics, essential parameters, such as normalized effective modal area, propagation length, group delay, and group velocity dispersion (GVD), are discussed in this section. Figure 6 depicts the variation of effective mode area w.r.t waveguide width (w). The numerical simulations show a normalized mode area of 0.05 with $h_{\text{slot}} = 25$ nm (SOLID line), which confirms the nanofocusing of quasi-TM mode in the slot regions of nanograting. With same slot height, the propagation length of 70 μm (SOLID BLUE) is achieved. The reliability study for proposed nanograting is performed by varying the slot height ($h_{\text{slot}}$) from 25 to 75 nm, keeping other parameters constant (follow Fig. 7). We have observed that smaller height slots (25 nm) support surface plasmons with a large electric field and better propagation length. With increased slot height, the fundamental modes start propagating in the higher-index

Table 1 Variables satisfying 1st order Bragg relation (Eq. 4)

| $\lambda$ (nm) | $n_{\text{eff}1}$ | $n_{\text{eff}2}$ | $p$ (nm) | $q$ (nm) |
|---------------|-----------------|-----------------|---------|---------|
| 1549.8 ($\lambda_{BG}$) | 3.48            | 1.493           | 228.38  | 10      |

Fig. 4 The 3D schematic diagram of dual-slot HPWG on-chip nanograting with period (p). Here, the inset shows the symmetric (even) mode and anti-symmetric (odd) mode near the output port (Poutput). Region I: Au–SiO2–Si–SiO2–Au, and region II: Au–Si3N4–Au

Fig. 5 a Dispersion plot for dual-slot HPWG nanograting and b transmission plot. Here, $N_g$ resembles the number of gratings

Fig. 6 Mode area and propagation length versus HPWG width (w)
Si waveguide and suffer more plasmonic losses. The various refractive index used for this study is listed in Table 2.

Figure 8a shows the linear variation of group dispersion with an increase in the group period \(p\). Here, the grating period is varied from 0.1 to 0.95 \(\mu\)m. Therefore, by varying grating period \(p\), we can effectively control the bandwidth range of optical device. Also, we found that, as the silicon nanowire height is increased, quasi-TM mode becomes more dielectric or photonic type, and starts propagating in the higher-index Si layer.

Next, dispersion is numerically characterized where phase values are taken from the time field monitor, followed by differentiation w.r.t angular frequency. Figure 8b shows that group velocity dispersion (GVD) is nearly zero over 1.45 to 1.6 \(\mu\)m. In this range, the maximum dispersion value is 9.75 ps\(^2\)/m. The comparison of the proposed nanoscale waveguide grating with the recently reported gratings is made in Table 3. Hence, the suggested nanograting is suitable for future optoelectronic components where low pulse broadening is required.

**Table 2** Refractive Index for Fig. 7 at \(\lambda = 1.55 \text{ \(\mu\)m}

| Material | Refractive Index |
|----------|------------------|
| Au       | 0.52406          |
| SiO\(_2\) | 1.444            |
| Si       | 3.4757           |
| Si\(_3\)N\(_4\) | 1.9963       |
Conclusion

In this paper, 3D Si–SiO₂–Au-based HPWG is simulated using RF module of COMSOL simulator. In contrast to the dielectric-loaded surface plasmon polariton (DLSPP) waveguide, the suggested photonic-plasmonic waveguide-based nanostructures show better performance in terms of normalized effective mode area (~0.05) and propagation length (~70 μm). These parameters are enhanced due to the less contact of bound modes with Au metal layer. Also, dual-slot HPWG nanograting is proposed with ultra-low dispersion (9.75 ps²/m) for high data rate applications. Hence, HPWG nanograting is suitable for the next generation on-chip IR band applications.

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