Theoretical Analysis of On-chip Vertical Hybrid Plasmonic Nanograting

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Research Article

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Abstract

a CMOS compatible photonic-plasmonic waveguide with nanoscale optical confinement has been proposed for the infrared (IR)-band applications. The design is based on the multilayer hybrid plasmonic waveguide (Si-SiO_2-Au) structure. The 3D-finite element method (FEM) numerical simulation of single slot HPWG confirms 2.5 dB/cm propagation loss and 15 um^{-2} confined intensity. Moreover, its application as dual-slot nanograting is studied which shows better propagation length and ultra-low dispersion near the 1550 nm wavelength. Hence, proposed low-dispersion design is suitable for future on-chip nanophotonic components in the IR band.

Introduction

Nowadays, CMOS technology make it possible to realize the ultrafast transistor with feature size less than 20nm. The on-chip integration of opto-electronic component follow the well-known Moore's law and the demand for smaller feature size is increasing day by day. The nanoscale devices with smaller dimension results in low power consumption & fast speed of operation with minimum delay. This delay limits the data handling capacity of the opto-electronic 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 Si layer is used to fabricate various Si transistors. This technology also overcomes the problem of diffraction limit faced by the fiber optics based optical components [1]. Till date, many plasmonic waveguide designs have been reported. Generally, plasmonic waveguides suffer from ohmic losses (due to metal layer), optical confinement and higher dispersion, as discussed in ref [2–4]. To overcome problems, multi-layer hybrid plasmonic waveguide (HPWG) design is proposed in this work. In contrast to the conventional plasmonic waveguide, HPWG waveguide demonstrate mode confinement & lower propagation losses.

In this paper Si-SiO_2-Au based plasmonic waveguide & nanograting is 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 in the top higher-index Si layer & lower-index SiO_2 slot. The work has been organized as follows. SECTION – II discusses device and simulation detail. SECTION – III analyzes all optical switching phenomenon in MISIM waveguide and discusses FKE induced tailoring of transmissions. Conclusions are made in SECTION-IV.

Simulation Setup & Mode Analysis

Fig. 1(a) shows the cross-sectional view of the proposed HPWG with Si-SiO_2-Au multi-layer structure. Gold (Au) is used as metal layer with 100 nm thickness (h_{Au}) and placed over silicon-dioxide substrate. Using Drude model, the dependence of imaginary part of permittivity on the photon energy for Au is plotted in Fig. 1 (b). Also, Si permittivity is defined through Drude model given in [5]. The refractive-index for the silicon-dioxide as slot and substrate are set by dispersion relation as per ref. [6]. The proposed waveguide is simulated with 3D-COMSOL multi-physics software using RF module [7]. The device is discretized using 1,285,045 triangular meshes. For optical waveguide modeling, mesh-type and geometric division are very important steps in device modeling. We have used element size than 0.255 *nm* for the Au metal layer. Furthermore, slot waveguide height (h_{Slot}) and width (W_{Slot}) are fixed to 100 nm, and 350 nm, respectively. With top silicon high-index layer and metal (Ag) layer, the lower-index slot region supports highly confined quasi-TM mode, see Fig 2a. Also, the dispersion relation of proposed HPWG waveguide is solved numerically (COMSOL simulations), following ref [7]. Fig. 2b shows the variation of propagation constant ($\beta = n_{eff} / k_0$) versus frequency. The cut-off frequency is nearly 110 THz, see Fig. 2b.

Further, RF module is used to perform the optimized study of normalized effective mode area (A_{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., $\lambda^2/4$. These parameters are derived using conventional waveguide theory. Here, A_{eff}, the effective mode area is defined as the ratio of total mode energy and peak energy density and formulated as,

$$A_{eff} = \frac{1}{Max\{W(r)\}} \iint W(r)\, dA \qquad (1)$$

Where the energy density W(r) is defined as,

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

E(r) and H(r) are the electric and magnetic fields, ε(r) is the electric permittivity, and μ0 is the vacuum permeability or magnetic constant. Also, the propagation length (L) of the bound modes is calculated using below relation:

$$L = \frac{1}{2\, Im\{\beta\}} \qquad (3)$$

According to fig. 2c, the normalized effective mode area and propagation length of suggested HPWG with h_{slot} = 25nm (SOLID line) is 0.05 and 60 um, respectively. The slot with smaller height, such as h_{slot} = 5nm, shows 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 fig. 2a & 3a. Fig. 3b shows that when width is more than 250 nm, the suggested waveguide suffers low losses. The 3D COMSOL simulations confirm propagation loss of 2.5 dB/cm and confined intensity of 15 um-2, respectively.

Hybrid Plasmonic Nanograting

In this section, we have performed the modeling of on-chip HPWG nanograting with filtering wavelength (λ_{BG}) of 1549 nm. The region 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 (see Eq. 4). Various variable (p, q, n_{eff1} and n_{eff2}) satisfying Eq. 4 are summarized in the TABLE – I to obey first-order Bragg relation (m=1) [11, 12]:

$$k_0[n_{eff1}(p-q)+n_{eff2}q]=(2m-1)\pi \tag{4}$$

TABLE 1. VARIABLES SATISFYING 1st ORDER BRAGG RELATION (EQ. 4).

λ (nm)	n_{eff1}	n_{eff2}	p (nm)	q (nm)
1549.8 (λ_{BG})	3.48	1.493	228.38	10

Further, we excite the TM mode near the input port P1. We observed that highly confined hybrid plasmonic mode (quasi-TM mode) start propagating through the low-index slot region (see inset of Fig. 4, symmetric & antisymmetric mode). The cut-off frequency is calculated as per the dispersion plot (fig. 5a). Fig. 5b shows the frequency behaviour of suggested HPWG nanograting with/without fins. For higher data rate, waveguide dispersion should be as low as possible to avoid the pulse broadening of the bound modes [10-12]. Nanoscale optical gratings are required for larger integration area in the modern photonics integrated circuits (PICs). The novel nanograting structure is proposed with periodic variation of refractive index (i.e., Region I & Region II, see fig. 4). The presence of grating in the Si layer results in controlling the bound modes effectively. Also, the suggested grating structure shows lower insertion losses (~ 20 % over the 1530 to 1560 nm wavelength window).

A nanophotonic Bragg grating based photonic-plasmonic low dispersion waveguide is analyzed using finite element method (FEM) based 3D-COMSOL Multiphysics simulator [7]. To study the transmission characteristics important parameters, such as normalized effective modal area, propagation length, group delay, & group velocity dispersion are discussed in this section. Fig 6 shows the variation of effective mode area w.r.t waveguide width (w). The numerical simulations demonstrate normalized mode area of 0.05 with h_{slot} =25 nm (SOLID line), which confirms the nano-focusing of quasi-TM mode in the slot regions of nanograting. Moreover, with same slot height the propagation length of 70 um (SOLID line)

Fig. 7a. shows the linear variation of group dispersion with increase in the group period (p). Here, the grating period is varied from 0.1 um to 0.95 um. Therefore, by varying grating period (p) we can effectively control the bandwidth range of the device. Also, we found that as the silicon nanowire height is increased, quasi-TM mode become more dielectric or photonic and propagate in the Si layer.

Next, dispersion is numerically characterized where phase values are taken from time field monitor, followed by differentiation w.r.t. angular frequency. Fig. 7b shows that group velocity dispersion (GVD) is nearly zero over 1.45 um to 1.6 um. In this range, the maximum dispersion value is 9.75 ps^2/m. Hence, the suggested nanograting is suitable for future opto-electronic components where low pulse broadening is needed.

Conclusion

In this paper, 3D Si-SiO_2-Au HPWG is simulated using RF module of COMSOL simulator. In contrast to dielectric-loaded surface plasmon polariton (DLSPP) waveguide, suggested photonic-plasmonic waveguide based nanostructures shows better performance in terms of normalized effective mode area (~ 0.05) & propagation loss (~ 70 um). These parameters are enhanced due to the less contact of bound modes with the metal layer. Also, dual slot HPWG nanograting is proposed with ultra-low dispersion (9.75 ps^2/m) for high data rate applications. Hence, nanograting is suitable for the next generation on-chip plasmonic integrated circuits (PICs).

Declarations

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Author Contribution Conceptualization and design of the work

Methodology: Samyuktha K, and Mandeep Singh. Formal analysis and investigation: Samyuktha K, and Mandeep Singh. Writing of the manuscript: Mandeep Singh. Writing—comments and suggestions: Samyuktha K.

Ethics approval: Not applicable

Consent to participate: Yes

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References

1. Gramotnev, D., Bozhevolnyi, S., “Plasmonics beyond the diffraction limit,” Nature Photon 4, 83–91 (2010).
2. F. P. Pile and D. K. Gramotnev, “Channel plasmon–polariton in a triangular groove on a metal surface,” Opt. Lett., vol. 29, no. 10, pp. 1069–1071, 2004.
3. T. Hill et al., “Lasing in metal-insulator-metal sub-wavelength plasmonic waveguides,” Opt. Express, vol. 17, no. 13, pp. 11107–11112, Jun. 2009.
4. F. P. Pile et al., “Theoretical and experimental investigation of strongly localized plasmons on triangular metal wedges for subwavelength waveguiding,” Appl. Phys. Lett., vol. 87, no. 6, 2005, Art. no. 061106.
5. Soref, R. E. Peale, and W. Buchwald, “Longwave plasmonics on doped silicon and silicides,” *Opt. Exp.* vol. 16, pp. 6507-6514, 2008
6. H. Malitson. Interspecimen comparison of the refractive index of fused silica, J. Opt. Soc. Am. 55, 1205-1208 (1965)
7. COMSOL Multiphysics *Users’ Manual*, COMSOL Inc
8. Singh, and A. Datta, “Modeling of a vertical hybrid plasmonic switch with VO_2 fin Bragg grating,” IEEE Photon. Technol. Lett., vol. 30, no. 11, pp. 997-1000, 2018.
9. Z. Alam, J. S. Aitchison and M. Mojahedi, "Theoretical Analysis of Hybrid Plasmonic Waveguide," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 19, no. 3, pp. 4602008-4602008, May-June 2013, Art no. 4602008
10. K. W. Lam, B. K. Garside, and K. O. Hill, "Dispersion cancellation using optical-fiber filters," Opt. Lett. Vol. 7, pp. 291-293, 1982.
11. Zhang, Y. Yue, R. G. Beausoleil and A. E. Willner, "Flattened dispersion in silicon slot waveguides," Opt. Express, vol. 18, pp. 20529- 20534, 9 2010.
12. Zhang, L. Cai, W. Bai and G. Song, "Flat Surface Plasmon Polariton Bands in Bragg Grating Waveguide for Slow Light," Journal of Lightwave Technology, vol. 28, pp. 2030-2036, 7 2010

Figures

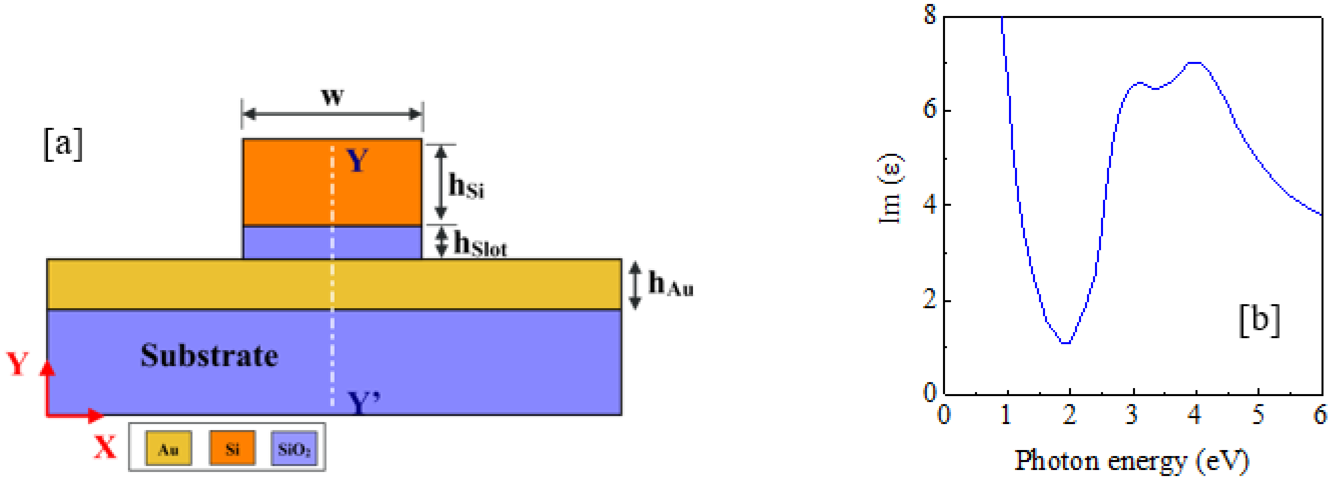

Figure 1

(a) The proposed Si loaded single slot vertical hybrid plasmonic waveguide (HPWG); (b) Variation of imaginary part of permittivity versus photon energy for Au. Here, hSi = 220 nm; hSlot = 50 nm; hAu = 100 nm; and w = 350 nm.

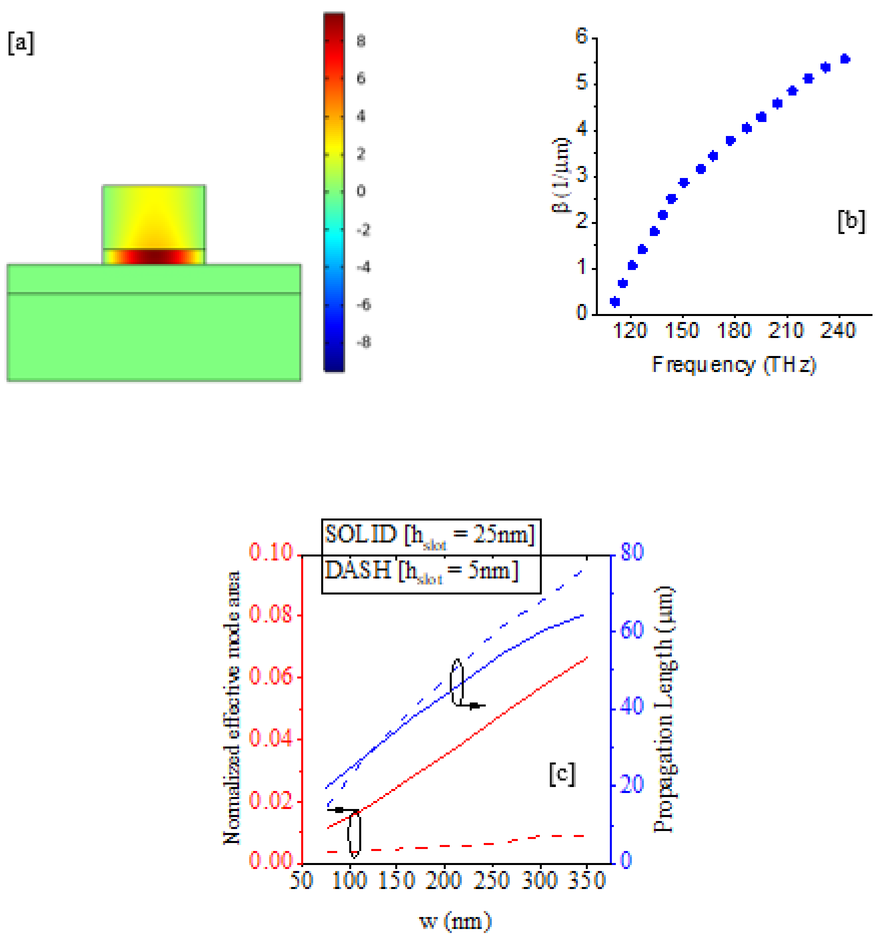

Figure 2

(a) Electric field [in V/m] distribution along YY'-axis near the output port P2 at λ=1550 nm. (b) Plot of propagation constant (β) versus frequency. and, (c) Mode area & propagation length versus width (w) of the single slot HPWG

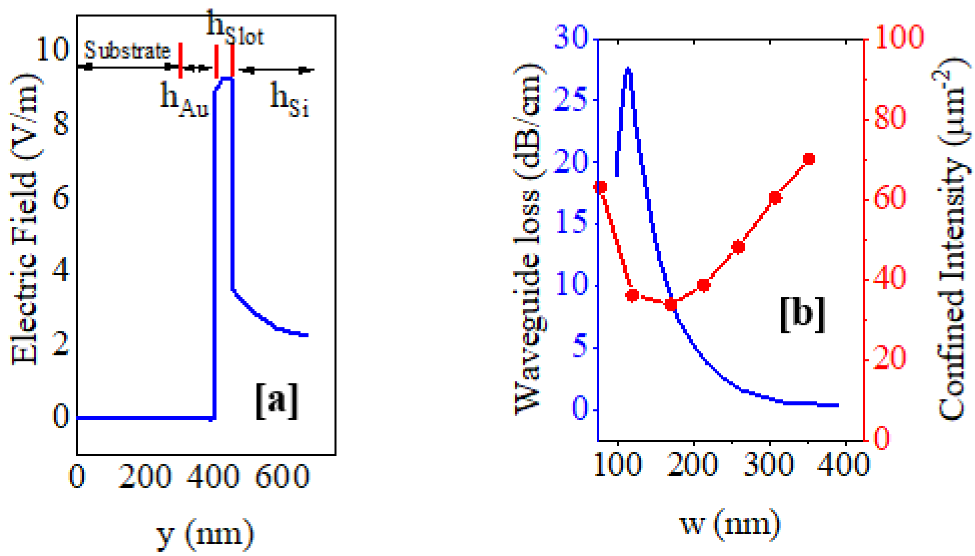

Figure 3

(a) The electric field line plot of the proposed Si-SiO2-Au waveguide, and (b) Waveguide loss & confined intensity versus width (w).

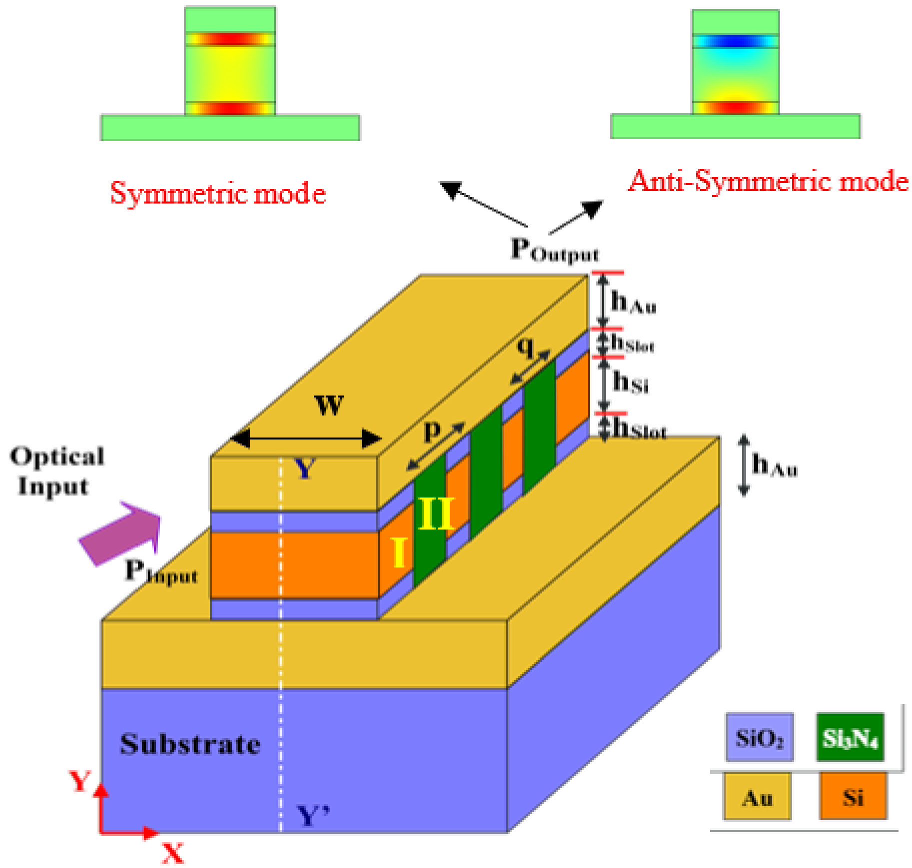

Figure 4

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

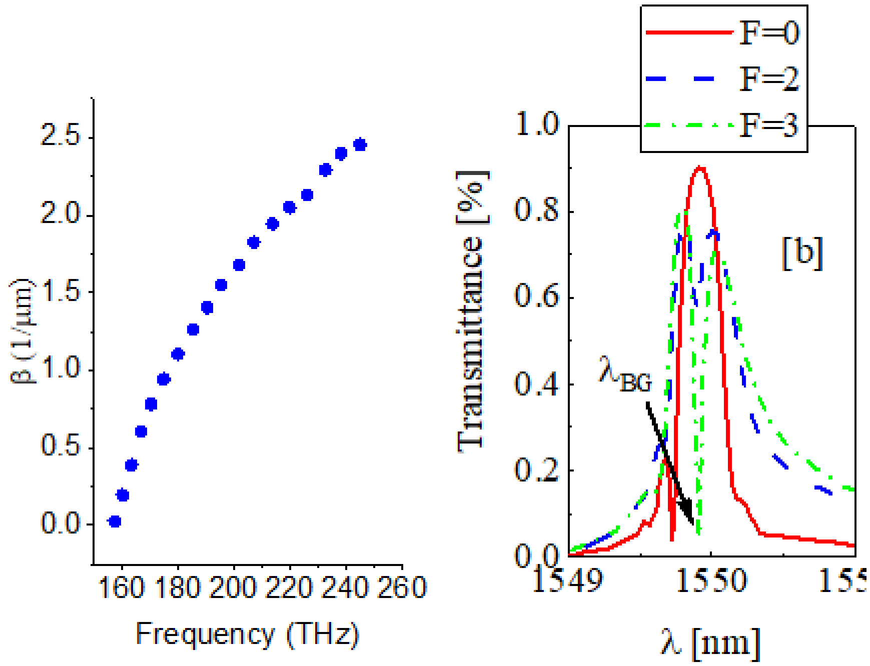

Figure 5

(a) Dispersion plot for dual slot on-chip nanograting; and (b) Transmission plot. Here “F” is the number of gratings.

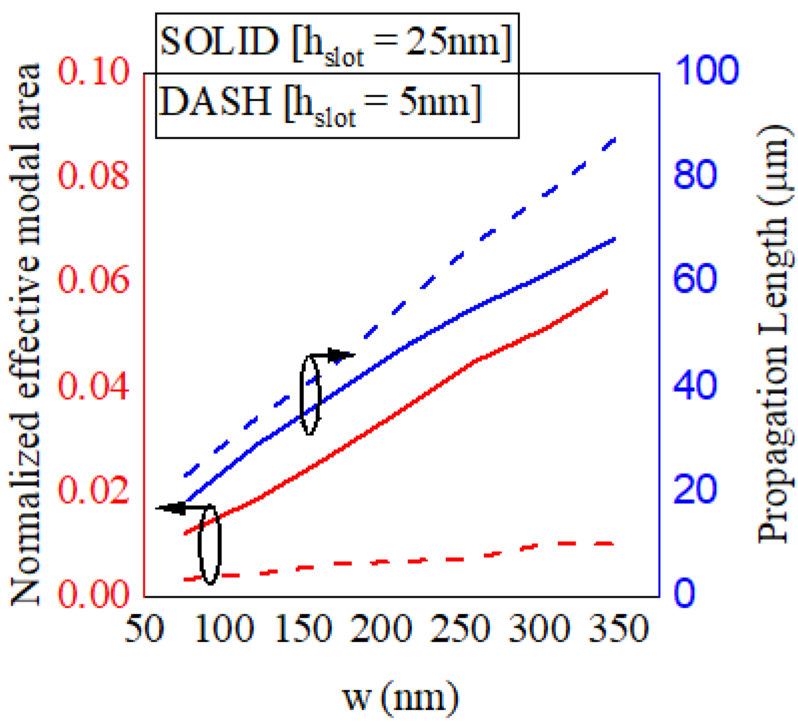

Figure 6

Mode area & propagation length versus width (w) of dual slot HPWG based nano-grating.

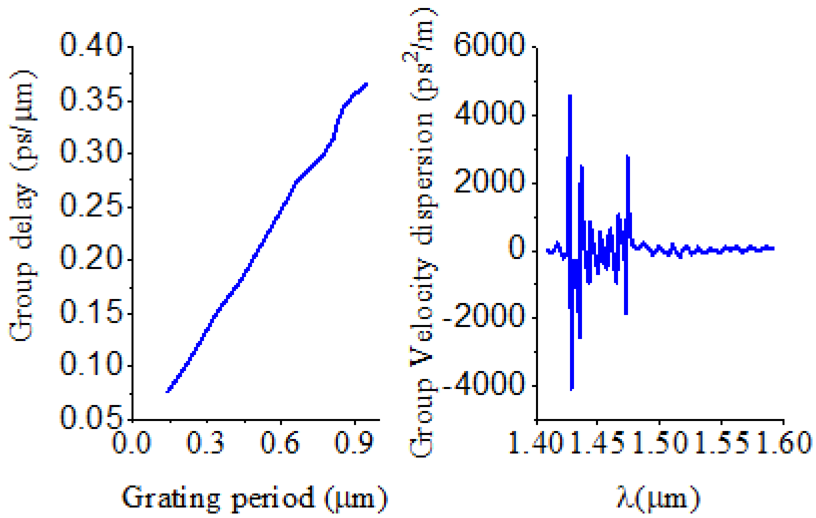

Figure 7

(a) Plot of group delay (ps/um) versus grating period (um) at λ= 1550nm.; (b) Group velocity dispersion for nanograting structure. Here period is (p) 228.38 nm and q is 10 nm, respectively.