Soliton-Induced Mid-Infrared Dispersive Wave in Horizontally-Slotted Si$_3$N$_4$ Waveguide

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ABSTRACT The flexibility of producing two dispersive waves (DWs) in silicon nitride (Si$_3$N$_4$) slot waveguide is demonstrated, by tailoring the slot features and the corresponding phase-matching condition. DWs are generated at visible and mid-infrared (mid-IR) wavelength regions, respectively. We obtain a broadband low normal dispersion region from 2 to 5.25 μm, which offers particular advantages for DW generation at mid-IR wavelength region. The long-wave dispersive wave (LWDW) can cover beyond 4 μm. This is the first time to illustrate the freedom of Si$_3$N$_4$ slot waveguide for DWs generation ever reported. A broadband spectrum can be extended from 0.5 to 4.5 μm at −30 dB level by launching a 1-kW 1550-nm hyperbolic secant input pump pulse to a 1-cm proposed waveguide. The newly formed spectrum has a high degree of coherence. This approach provides more flexibility for frequency conversion, and has the advantages for biophotonics, optical sensing, chip-integrated spectroscopy, health and environmental monitoring.

INDEX TERMS Nonlinear optics, chromatic dispersion, silicon photonics, integrated optics.

I. INTRODUCTION

In the past decade, several applications such as astronomical spectrograph calibration [1]–[3], biophotonics [4], and optical clocks [5] require light sources in the visible wavelength range. The mid-infrared (mid-IR) wavelength region, is of great interest for optical sensing, thermal imaging [6]–[8], and environmental monitoring [9]. Especially, the availability of direct mid-IR generation is limited, i.e., cascaded quantum lasers [10] and inter-band lasers [11]. A broadband spectrum covering from visible to mid-IR region offers particular advantages for these applications. Dispersive wave (DW) generation is one of the effective mechanisms to generate a broadband spectrum. DW generation is the process of a fundamental soliton shedding the energy to a specific wavelength based on the phase-matching condition when it is affected by higher-order dispersion [12]. Conventionally, DWs are emitted in the normal dispersion region when input pulse is pumped in the anomalous dispersion regime [13]–[17]. These results further indicate that DW generation is another candidate to obtain extended spectra with high coherence.

Compared with fiber, photonic integrated circuits (PICs) offer important advantages due to the smaller device footprint. Compatibility of PICs with the complementary metal–oxide–semiconductor (CMOS) technology is beneficial for device cost and fabrication precision with a large scale [18], [19]. Additionally, silicon waveguide is not transparent at wavelengths below 2.2 μm due to two-photon absorption (TPA) [20], [21], hence it generally limits the visible spectral components generation. Silicon nitride (Si$_3$N$_4$) waveguides is a promising candidate to realize broad spectral coverage from the visible to the mid-IR [22]. Meanwhile, slot waveguide is widely explored to tailor various properties for on-chip elements [23]–[25], including dispersion manipulation [26]–[28], supercontinuum (SC) generation [22], [29], and other applications [23], [30], [31]. The slot layer is...
considered as an additional freedom, which could be beneficial for performing a large flexibility for tuning various optical nonlinearities over a broad bandwidth. Thus, compared with the previous reports on DWs generation [13]–[17], our work could provide the method of extending the generated DW to longer wavelength regime without increasing the device footprint.

In this work, we illustrate the design freedom of DW generation based on a Si$_3$N$_4$ horizontal slot waveguide. The proposed waveguide can be fabricated as following [25], [32]: the SiO$_2$ bottom cladding layer results from the wet thermal oxidation of silicon substrate. Based on low-pressure chemical vapor deposition (LPCVD)/plasma enhanced chemical vapor deposition (PECVD), lower Si$_3$N$_4$ layer, slot SiO$_2$ layer, and higher Si$_3$N$_4$ layer can be deposited respectively. After etching and resist removal, the designed slot waveguide structure can be eventually obtained. Moreover, the position of the DWs could be controlled by dispersion tailoring and the phase-matching condition engineering. By pumping in the telecommunication bands, two DWs are emitted at visible and mid-IR wavelength regions. The designed waveguide features a broadband low normal dispersion from 2 to 5.25 μm, which is beneficial for mid-IR DWs emission at longer wavelengths. To the best of our knowledge, this is the first report of investigating the advantages of Si$_3$N$_4$ slot waveguides in DWs management, and the long-wave dispersive wave (LWDW) enables to cover beyond 4 μm. The spectrum covers from 500 to 4500 nm via two DWs generation, and the whole spectrum is shown to have a high degree of coherence. A highly efficient nonlinear conversion is realized from visible to mid-IR through this approach. Moreover, it provides the possibility for having an efficient, compact, and coherent broadband light source, and illustrates the flexibility of DWs generation in the Si$_3$N$_4$ slot waveguide.

FIGURE 1. Schematic diagram of DW generation process in the proposed Si$_3$N$_4$ slot waveguide. Visible DW and mid-IR DW generation through phase matching to the soliton pulse seeded by pumping in the anomalous GVD regime.

II. RESULTS

A. WAVEGUIDE STRUCTURE AND CONCEPT

The schematic diagram of DW generation in Si$_3$N$_4$ slot waveguide is shown in Fig. 1. As a short pulse propagates along the proposed waveguide, the output spectrum is broadened with DW generation. In general, when the solitons are perturbed by third- or higher-order dispersion, DWs are generated at specific wavelengths in normal dispersion regime, and the corresponding wavelengths are determined by phase-matching condition. Strip waveguide has the limitation of design freedom because only the waveguide width and height could be adjusted. As depicted in Fig. 1(a), the waveguide width $W$, waveguide height $H$, upper Si$_3$N$_4$ thickness $H_u$, middle SiO$_2$ slot thickness $H_s$, and lower Si$_3$N$_4$ thickness $H_l$ are adjustable geometric parameters, which extend the flexibility of nonlinear effects. The phase-matching condition could be engineered by utilizing the designed waveguide, and then the position of DWs could be further tailored. The visible and mid-IR DWs are generated by optimizing the phase matching conditions, and such phase matching is further extended to 5 μm. Therefore, visible and mid-IR DW generation are expected in such waveguides through pumping in the anomalous GVD regime, as schematically indicated in Fig. 1.

When the following phase-matching condition is satisfied [12], the solutions determine the frequencies of one or more DWs,

$$\beta(\omega) = \beta(\omega_s) + \beta_1(\omega - \omega_s) + \frac{1}{2} \gamma P_s$$

(1)

where $\omega_s$ and $\omega_k$ represent the frequencies of the DWs and soliton, and $\beta(\omega)$ represents the propagation constant. The constant term consists of the Kerr nonlinear coefficient $\gamma$ and soliton peak power $P_s$. Eq. (1) could be expressed as the phase mismatch between the DW and the soliton:

$$\Delta \beta(\omega) = \beta(\omega) - \beta(\omega_s) - \beta_1(\omega - \omega_s) - C_0$$

$$= \sum_{n=2}^{\infty} \frac{(\omega - \omega_s)^n}{n!} \frac{d^n}{d\omega^n} \beta(\omega_s) - C_0$$

(2)

where $1/2 \gamma P_s$ is defined as $C_0$. The nonlinear contribution of constant term is relatively small for the soliton phase, and the constant term could be negligible due to the pulse distortion. The position of DWs could be tuned by chromatic dispersion (CD) and phase-matching condition engineering. In addition, the intrapulse Raman scattering could be negligible in Si$_3$N$_4$ waveguide.

B. DISPERSION AND NONLINEARITY PROPERTY

By using the Sellmeier equations [33], [34], we calculate the wavelength-dependent material refractive indices of Si, SiO$_2$ and Si$_3$N$_4$. The complex effective refractive indices of fundamental transverse magnetic (TM) mode at different
wavelengths can be obtained by using a full-vector finite-element-method (FEM). The CD can be obtained from the real part of the effective refractive index.

\[
D = -\frac{\lambda}{c} \left( \frac{d^2 \text{real}(n_{\text{eff}})}{d\lambda^2} \right)
\]

where \( D \) is the CD parameter and \( c \) is the speed of light in the vacuum. \( \lambda \) represents the wavelength, and \( n_{\text{eff}} \) is the effective refractive index. As shown in Fig. 2(a), the CD of Si\(_3\)N\(_4\) horizontal slot waveguide is engineered to exhibit three zero dispersion wavelengths (ZDWs) at 1.1 \( \mu \)m, 2.02 \( \mu \)m, 5.25 \( \mu \)m, respectively. The pump wavelength is 1.55 \( \mu \)m, which experiences anomalous dispersion of 68.61 ps/(nm \( \cdot \) km). The dispersion is normal from 2.02 to 5.25 \( \mu \)m, and the average dispersion is \(-32.59 \text{ ps/(nm} \cdot \text{km)}\) over a 3.23-\( \mu \)m wavelength range, which provides the potential possibilities to generate DW in this broadband normal dispersion regime. Figure 2(b) also shows the nonlinear coefficient \( \gamma \) versus wavelength using a full-vector model [35], and use the measurement data of nonlinear refractive indices \( n_3 \) for Si\(_3\)N\(_4\) and SiO\(_2\) in [36], [37]. The nonlinear coefficient \( \gamma \) decreases with the wavelength from 3.27 to 0.023 /W/m. At 1.55 \( \mu \)m, the effective mode area is 1.36 \( \mu \)m\(^2\), and the corresponding nonlinear coefficient \( \gamma \) is 0.72 /W/m. Our simulation results show that the confinement losses are 7.84 dB/cm at 4 \( \mu \)m and 41.13 dB/cm at 4.5 \( \mu \)m, respectively. The confinement loss could be decreased by further adjusting the geometric parameters of the waveguide.

**FIGURE 2.** (a) CD, (b) nonlinear coefficient and loss in the proposed waveguide with the parameters of \( W = 1400 \) nm, \( H_u = 1120 \) nm, \( H_s = 250 \) nm, \( H_l = 1330 \) nm.

**C. DWS ENGINEERING**

In this part, we demonstrate the ability of mid-IR DWs generation based on a 1550-nm input pulse pumping in the anomalous-GVD regime, and the spectra have two DW emissions. Moreover, we discuss the dependence of the phase-matching points on the waveguide parameters in details, and verify it through calculating the corresponding spectra based on the generalized pulse-propagation equation (GNLSE) [12].

\[
\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - i \int_0^\infty \int_0^\infty R(t') |A(z, t - t')|^2 dt'
\]

where \( A \) is the electric field envelope, \( \omega_0 \) is the carrier frequency, \( \alpha \) is the loss. \( \beta_n \) represents the \( n \)-th order dispersion coefficient. The frequency dependence of Kerr nonlinear coefficient \( \gamma \) also can be expanded as a Taylor series about the center frequency \( \omega_0 \), i.e., the \( n \)-th order coefficient of nonlinearity \( \gamma_n \) is defined as:

\[
\gamma_n = \left( \frac{d^n \gamma}{d \omega^2} \right)_{\omega = \omega_0}
\]

The integral of \( R(t) \) represents intrapulse Raman scattering, and \( \beta_n \) is the Raman response function, which can be neglected in Si\(_3\)N\(_4\) waveguides [19], [38]. In the simulation, we have all-order dispersion terms and 6-th order nonlinear of coefficient included. In addition, we consider the wavelength dependence of the dispersion, nonlinearity, and loss. We use the split-step Fourier method to calculate the GNLSE. The core technique of this method is to divide the propagation length into many small segments, and then to assume that the dispersion and nonlinear effects act independently in each segment. A 100-fs chirp-free hyperbolic secant input pulse is launched into the 1-cm length slot waveguide, and its peak power is 1 kW.

1) SLOT WAVEGUIDE WIDTH (\(W\))

Firstly, the waveguide width \( W \) is tuned from 1350 to 1450 nm as illustrated in Fig. 3(a), while maintaining the overall waveguide height, slot thickness, and upper Si\(_3\)N\(_4\) thickness as \( H = 2700 \) nm, \( H_s = 250 \) nm, \( H_u = 1120 \) nm, respectively. The position of short-wavelength dispersive wave (SWDW) is relatively stable, whereas the LWDW moves towards longer wavelength. The spectra of different waveguide widths are depicted in Fig. 3(b). The moving of the generated DWs agrees well with that of the LWDW. When \( W \) is 1450 nm, the spectrum extends from visible (500 nm) to mid-IR (4500 nm) at \(-30 \text{ dB level involving two DWs.} \)

2) WAVEGUIDE HEIGHT (\(H\))

Additionally, the waveguide height \( H \) can be used to tailor the phase-matching point as well. In the next step, we keep the waveguide width \( W \) as 1400 nm and the upper Si\(_3\)N\(_4\) thickness as 1120 nm with 250-nm slot thickness \( H_s \), but increase the waveguide height \( (H) \) from 2650 to 2750 nm. As illustrated in Fig. 4(a), the phase mismatch curve is
more sensitive to the height changing. The fundamental TM mode distribution is $y$-polarized, so the position of long-wavelength phase-matching point is more sensitive to the structure parameters along the $y$-axis, such as the waveguide height $H$. The phase-matching point at long wavelength region shifts towards the pump wavelength, and the LWDDW is closer to the center wavelength in Fig. 4(b), as the waveguide height ($H$) decreases. In order to generate a DW at longer wavelength, considering the footprint of waveguide and spectrum quality, we choose the overall waveguide height as 2700 nm.

3) UPPER ($H_u$) AND LOWER ($H_l$) Si$_3$N$_4$ THICKNESS OF THE SLOT WAVEGUIDE
Different from tailoring the DWs by changing device overall footprint, we enable to adjust the DWs position by utilizing the slot layer, as shown in Fig. 5(a). In this way, the waveguide size could be maintained. By keeping the cross section at $1400 \times 2700 \, \mu m^2$, the upper Si$_3$N$_4$ thickness $H_u$ is adjusted in a step of 20 nm for further finely tuning the position of phase-matching point. $H_u$ is remained as 250 nm. As predicted by the phase-mismatch curve, one can see in Fig. 5(b) that the DWs can be generated at longer wavelength by decreasing the $H_u$, and the spectrum is red shifted. Considering the quality of the spectra, $H_s = 1120$ nm is a better choice.

4) SLOT THICKNESS ($H_s$)
We further study the effects of the slot thickness $H_s$ on the phase-matching condition. The slot thickness $H_s$ changes from 240 to 260 nm, and the upper Si$_3$N$_4$ thickness $H_u$ remains to be the optimized value as 1120 nm. As illustrated in Fig. 6(a), the phase-matching points can be slightly engineered through tuning $H_s$. The long-wave phase-matching point is closer to the pump wavelength as the slot layer is thicker. Under the premise of typical geometric parameters ($W = 1400$ nm, $H_u = 1120$ nm, $H_s = 250$ nm, $H_l = 1330$ nm), the Si$_3$N$_4$ horizontal slot waveguide produces the mid-IR DW up to 4500 nm in Fig. 6(b). The spectrum is broadened with the generation of two obvious separated peaks at 500 and 4500 nm, respectively. As shown in Fig. 7, it is obvious that the spectrum intensity gets higher as the peak power $P$ increases.
Table 1 summarizes the comparison with the other two DWs generation results in silicon and Si$_3$N$_4$ waveguides on silicon dioxide insulator. The star sign in the “waveguide” column indicates the Si$_3$N$_4$ waveguides with SiO$_2$ cladding. Two DWs are generated in these works through pumping in the anomalous dispersion regime, i.e., SWDW and LWDW are generated on both wavelength sides of the pump pulse. We summarize the position of two DWs and the corresponding SC bandwidth. Silicon suffers from the high nonlinear absorption due to TPA in telecommunication bands with wavelengths $< 2.2$ $\mu$m. It is difficult to generate the SWDW at visible wavelengths in silicon waveguides. This is addressed by using Si$_3$N$_4$ waveguide in some previous reports. One can see that the SWDW wavelength can be expanded to 0.5 $\mu$m, but the LWDW wavelength is only up to 3 $\mu$m. In [39], the phase matching condition is extended to 4 $\mu$m by tuning waveguides width, nevertheless, the flexibility of DWs tailoring is limited, and the coherence decreases obviously in multiple locations over the spectrum. Here, by leveraging a large flexibility of DWs engineering in the proposed Si$_3$N$_4$ slot waveguide, our work enables the generation of SWDW at 0.5 $\mu$m and LWDW beyond 4 $\mu$m. A SC extending from 0.5 $\mu$m to 4.5 $\mu$m at $-30$ dB level can be generated by pumping at telecommunication bands ($W = 1450$ nm, $H_u = 1120$ nm, $H_s = 250$ nm, $H_l = 1330$ nm). This work provides the possibilities to extend the phase matching condition to 5 $\mu$m through reduced loss.

Pumping in the anomalous-GVD regime (1550 nm) results in the occurrence of soliton fission. The soliton order of the input pulse $N$ is calculated, which is determined by the following expression described in [12]:

$$N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$  \hspace{1cm} (6)

where $P_0$ is the input peak power, $T$ is the pump pulse duration, and the soliton number of the input pulse is relatively...
To assess the spectra coherence for the process of two DWs generation, we examine the complex degree of the first order coherence, which demonstrates the incoherent state of the coherence, which corresponds to perfect coherence. The inserted figure magnifies the edges of the coherence, which shows the incoherent state of the soliton fission and the visible and mid-IR DWs generation process, and the large loss near 5 µm can be observed.

D. COHERENCE

To assess the spectra coherence for the process of two DWs generation, we examine the complex degree of the first order coherence for the generated spectra using 40 simulations under identical conditions, except for the stochastic quantum noise of the input pulse [45], [46]. The degree of coherence is calculated as [12]:

\[
g_{12}(\omega) = \frac{\langle |\tilde{A}_1(L, \omega)\tilde{A}_2(L, \omega)|^2 \rangle}{\langle |\tilde{A}_1(L, \omega)|^2 \rangle \langle |\tilde{A}_2(L, \omega)|^2 \rangle}^{1/2}
\]

where \( \tilde{A}_1 \) and \( \tilde{A}_2 \) are the Fourier transforms of two neighboring pulses, and the angle brackets denote an average over the entire ensemble of pulses. In Fig. 9(a), \( g_{12}(\omega) = 1 \) is valid over the entire bandwidth, which corresponds to perfect coherence. The inserted figure magnifies the edges of the coherence, which shows the incoherent state of the soliton fission, which demonstrates the incoherent state of the coherence, which corresponds to perfect coherence. The inserted figure magnifies the edges of the coherence, which shows the incoherent state of the soliton fission and the visible and mid-IR DWs generation process. As seen in the temporal and spectral-evolution plot of Fig. 8, we could notice the soliton fission and the DWs generation process, and the large loss near 5 µm can be observed.

By taking advantage of this flexibility, one could realize the nonlinear process of two DWs generation by pumping at telecommunication wavelengths, and the DWs locate in both the visible and the mid-IR range. Benefiting from the broadband normal dispersion region from 2 to 5.25 µm, the possible position of the mid-IR DW generation is ultrawide, and the DW is expanded to beyond 4 µm. The spectrum depends on high-order soliton fission and two DWs generation. A coherent SC could be generated from 0.5 to 4.5 µm, by pumping a 100-fs 1-kW input pulse in 1-cm Si₃N₄ slot waveguide. Our technique offers the possibility to form a high-power coherent source with various applications, including precision metrology, spectroscopy, and optical clocks.

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