Broadband Supercontinuum Generation in Mid-Infrared Range (0.8 μm – 4.5 μm) Using Low Power Dispersion-Engineered CMOS Compatible Silicon-Rich Nitride (SRN) Waveguide

Abstract—**We numerically modeled a complementary metal-oxide-semiconductor (CMOS) compatible 5-mm-long rectangular waveguide for broadband mid-infrared (MIR) supercontinuum (SCG) generation. The waveguide is constituted using Si-Rich Nitride (SRN) as a core and $LiNbO_3$ glass for its top and bottom claddings. The proposed waveguide structure is optimized for pumping only in the anomalous dispersion regime. Numerical analysis reveals that a wideband SCG into the MIR spanning the wavelength 0.8 μm to 4.5 μm could be generated by the proposed geometry using a very low pulse peak power of 40 W having width of 50-fs employing pump at 1.55 μm wavelength.**

Index Terms—**Silicon-rich Silicon nitride, Planar waveguide, Dispersion, Supercontinuum generation,**

I. Introduction

Generation of supercontinuum (SCG) has drawn a significant attraction because of having capability of creating a very broad continuous spectrum and having important applications in spectroscopy, optical coherence tomography (OCT) and biomedical applications [1]. Developed technology in microstructured fiber design and fabrication ensures the improvement of SCG source which can operate in the extended region from deep ultraviolet (UV) to mid-infrared (MIR) region [2]. Recently Silicon-On-Insulator (SOI) technology facilitates the use of Complementary Metal Oxide Semiconductor (CMOS) fabrication effectively to build low cost and scalable integrated optical components similar to silicon photonics which is a promising candidate for broadband supercontinuum (SC) generation in the MIR [3].

Silicon rich nitride (SRN) consist of 65% Silicon (Si) and 35% Nitrogen (N) contains a huge bandgap of 2.05 eV which eliminates the Two-Photon Absorption (TPA) at 1.55 μm [4]. The Kerr nonlinearity of 2.8 $\times$ 10^{13} cm^2/W (4 times larger than that of silicon) and refractive index of about 3.1 to tailor dispersion [5]. The loss is taken for merely material by ignoring substrate linkage is 6 dB/cm since of Si-H bonds formation for chemical vapor deposition [6].

Recently a few research groups have demonstrated SCG generation using SRN waveguides [5], [7]]. Ting *et al* [5] demonstrated 1.13 μm to 1.75 μm spectrum broadening in SiO_2 overclad SRN waveguide SiO_2 is used as cladding by pumping at 1.55 μm with 500 fs duration at peak power 140 W. Liu *et al* [7] demonstrated spectrum spanning 0.82 μm to 2.25 μm through 10 mm long SRN waveguide using Er-Fiber laser pumped at 1.55 μm as the center frequency with 105 fs duration at peak power 1330 W theoretically and experimentally.

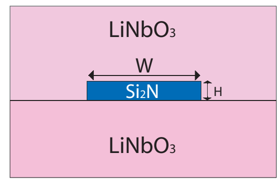


Fig. 1: The schematic diagram of proposed SRN waveguide structure with H = 0.5 μm and W = 3 μm.

In our proposed work, a 5 mm-long dispersion-engineered CMOS compatible SRN waveguide for broadband SCG generation in anomalous dispersion region is numerically investigated. A spectrum broadening from 0.8 μm to 4.5 μm is observed by pumping at the wavelength of 1.55 μm with a TE polarized 50 fs duration full-width half maximum sech pulse at a peak power of 40 W. It is worth to mention that most of the aforementioned work described earlier, researchers used SiO_2 as cladding for the modeling of SRN waveguides. Since SiO_2 affects by high material absorption loss in the MIR region more than 2.3 μm and $LiNbO_3$ glass as cladding has transparency beyond 4 μm, thus we considered $LiNbO_3$ as cladding in proposed CMOS compatible waveguide design. To the best of our knowledge, it is the first time proposed $LiNbO_3$ claded SRN waveguide for SC generation.

II. Modeling and Method

The geometric structure of the proposed rectangular waveguide made of SRN as a core and $LiNbO_3$ glass as a cladding is shown in Fig. 1. In the simulation, the necessary linear refractive indices of Si_2N and $LiNbO_3$ glasses are calculated using the Sellmeier Eqs. 1 and 2 that are taken from [4] and [8], respectively.

$$n(\lambda) = 1 + \sqrt{1 + \sum_{k=1}^{N} \frac{\alpha_k \lambda^2}{\lambda^2 - \beta_k^2}} \tag{1}$$

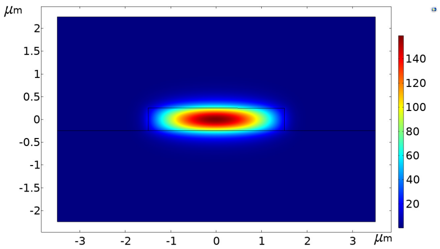


Fig. 2: Field profile at 1.55 μm of proposed waveguide for fundamental quasi-TE mode.

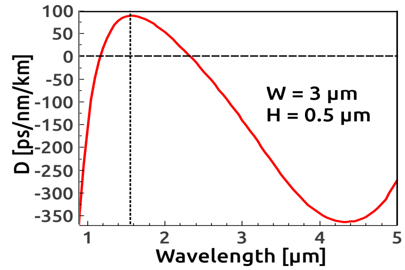


Fig. 3: The tailored GVD curve for the proposed SRN waveguide structure. Vertical dotted line represents the pump wavelength of 1.55 μm.

$$n(\lambda) = \sqrt{1 + \sum_{k=1}^{N} \frac{\alpha_k \lambda^2}{\lambda^2 - \beta_k^2}} \quad (2)$$

The respective value for described coefficients α, β in Equation 1 and Equation 2 are given in table I.

TABLE I: Sellmeier Coefficients

Materials	SRN (Si_2N)		$LiNbO_3$	
N	α_k	β_k	α_k	β_k
k=1	2.21715	0.0632602	2.67334	0.01764
k=2	1.12108	0.249134	1.2290	0.054914
k=3	24.8224	250.091	12.614	474.600
k=4	17.6617	251.079	-	-

The numerical analysis is performed by using the finite element analysis (FEA) based simulation software COMSOL Multiphysics. Initially all the mode propagation constant $\beta(\omega)$, have to be calculated for fundamental quasi-TE mode using COMSOL, then using these values to calculate any refractive index distribution for a certain range of the desired wavelength. The field pattern for fundamental quasi-TE mode is shown in Figure 2 for the proposed waveguide geometry of thickness, H = 0.5 μm and width, W = 3 μm at 1.55 μm pump wavelength. The group velocity of dispersion (GVD) which is a very important parameter is calculated by using the following Eq. 3 [9]

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 Re(n_{\text{eff}})}{d\lambda^2} \quad (3)$$

Broadband MIR SC generation for the proposed waveguide have been studied by using the Generalized Nonlinear Schrödinger Equation (GNLSE) for anomalous dispersion of single-polarization propagation [10]. Raman effect of SRN is very low so that it can be neglected in SRN waveguide simulation [11].

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A + \sum_{k \geq 2}^{12} \frac{i^{k+1}}{k!} \beta_k \frac{\partial A^k}{\partial T^k} + i\gamma(|A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial z} |A|^2 A) \quad (4)$$

In GNLSE Equation, A(z,T) is denoted the pulse envelops which evolves throughout wavelength of waveguide in a retarded time frame with reference $T = t - \beta_1 Z$ moving at the group velocity $v_g = \frac{1}{\beta_1}$. β_k (k$\geq$2) is the higher order Taylor series expended dispersion coefficients around the center angular frequency ω_0 and associated attenuation of SRN waveduide is α. The nonlinear parameter is described as $\gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}}$ where n_2 is Kerr-nonlinearity at pump wavelength and $A_{\text{eff}} = \frac{(\int\int |E^2| dxdy)^2}{(\int\int |E|^4 dxdy)}$ is mode effective area for fundamental mode [12].

III. Numerical results

To get a compact and efficient SCG spectrum at the waveguide's output, the GVD is the most important key parameter. For the expansion of SCG spectra UV to the MIR region, a planar waveguide made of SRN can be modeled for pumping in either normal or anomalous dispersion region. Initially, the detail numerical analysis is carried out for several geometries by changing the waveguide transverse dimensions such as width (W) and height (H) for employing pump at 1.55 μm to obtain expanded SCG beyond the MIR region. Since the

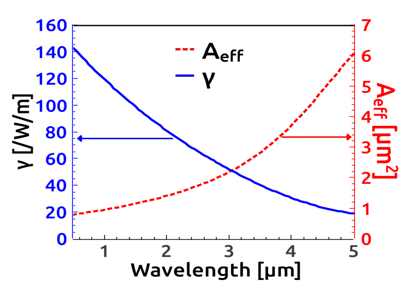


Fig. 4: Mode effective area and nonlinearity curves of proposed SRN waveguide structure with H = 0.5 μm and W = 3 μm.

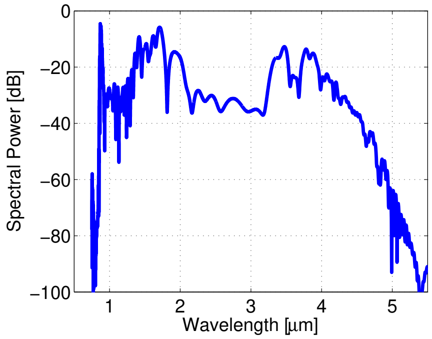
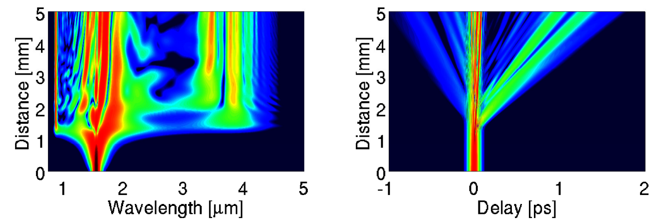


Fig. 5: SC spectrum at the waveguide output is shown by pumping at 1.55 μm in anomalous dispersion region with a low input peak power of 40 W.



(a) (b)

Fig. 6: (a) Spectral and (b) Temporal density evolutions are plotted in 1.55 μm pump wavelength.

zero-dispersion wavelength (ZDW) is playing an vital role in the SC generation, the waveguide is engineered in such a way that the pump source can be employed close to ZDW at the anomalous region for extending the SCG beyond SRN material transparency limit > 5 μm. The transverse electric field (TE) for fundamental quasi mode was used for designing the model. The electric field plot for fundamental quasi-TE mode is described in Fig. 2 obtained from COMSOL. The maximum electric field value is obtained 157 V/m in core confinement of fundamental mode and decreased it to a minimum of 20 V/m in the cladding region. The GVD was calculated by using the Eq. 3 of an effective refractive index for wavelength region 0.5 μm to 5 μm through COMSOL. To obtained n_{eff} value, the Sellmeier Equations for SRN and $LiNbO_3$ depicted in Eqs. 1 and 2 were used. The GVD curve in Fig. 3 is obtained for waveguide structure of H = 0.5 μm, W = 3 μm and the calculated dispersion is 89.4 ps/nm/km at the pump wavelength of 1.55 μm. From the figure, it is noted that two ZDW at 1.2 μm and 2.5 μm are obtained which play a significant role for the expansion of SCG in the longer wavelength region.

The GNLSE equation is solved by using a symmetrized split-step Fourier method [9]. For simulation, 2^{13} grid points are taken. The time step is chosen 2.76 fs for eliminating negative frequency generation in the frequency grid. In the direction of propagation, the axial number of steps is considered as 100 000 with a step size of 0.1 μm. The waveguide is modeled for pumping at 1.55 μm wavelength with a TE polarized 50 fs duration sech pulse at a pulse peak power of 40 W. The spurious-free spectral broadening is ensured by calculating the higher-order $\beta(\omega)$ up to 12th order. Mode effective area (A_{eff}) and nonlinear coefficient (γ) for the proposed structure for the wavelength range of interests are calculated by using FEM mode solver which is depicted in Figure 4. The estimated A_{eff} and γ at 1.55 μm are calculated as 1.17 μm^2 and 96.81 /W/m where the nonlinear parameter n_2 = 2.8 $\times$ 10^{-13} cm^2/W and propagation loss α = 6 dB/cm are taken from [4].

Figure 5 depicts the SCG spectrum spanning from near-IR to MIR for the proposed geometry where it can be observed that spectral broadening occurs from 0.8 to 4.5 μm (-40 dB equivalent level from peak). The corresponding spectral and temporal evolutions are depicted in Figs. 6a and 6b from which it can be seen that the soliton fission occurs at a length of 1.2 mm along the waveguide and the number of solitons induced is 5. Since there is no Raman scattering, no Raman induced self-frequency shift is evolved. The self phase modulation is observed in the broadening near the pump wavelength due to applied self-compression of given pulses. Two dispersive waves (DWs) have appeared in short and long-wavelength side of the spectrum due to the existence of two ZDWs in the respective GVD curve described in Figure 3. The first DW is located at around 900 nm and the center of long wavelength DW is located approximately at around 4 μm.

IV. Conclusion

In this work, a CMOS-compatible novel planar structure using SRN material is proposed for broadband SCG in the MIR. A 5-mm-long on-chip compatible geometry, which is modeled using Si_2N as a core and $LiNbO_3$ glass for its upper and lower claddings, generates an SC spanning up to 4.5 μm into the MIR with a very low pulse peak power of 40 W employing pump at 1.55 μm wavelength. This is the widest SCG spanning, to the best of our knowledge, in the MIR using planar SRN waveguide which can be used for several MIR region applications.

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