Blue-Yellow-Red Multi-color Si-rich SiO_x Strip-Loaded Waveguide Amplifier

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Abstract: Si-nanocrystal incorporated Si-rich SiO_x strip-loaded waveguide amplifiers grown by detuning N_2O/SiH_4 fluence ratio and RF power are demonstrated with blue, yellow, and red multi-color amplified-spontaneous-emission and gain coefficients of 160, 70 and 45 cm^{-1}.

OCIS codes: (230.7370) Waveguides; (130.5990) Semiconductors; (160.4236) Nanomaterials; (140.4480) Optical amplifier.

1. INRINTRODUCTION

Either increasing the transistor quantity or introducing the optical interconnect is the alternative way toward enhancing the data processing speed and data transmission rate at the chip level. In the former case, the interior Cu bonding wire based transmission lines still cause the RC delay to limit the transition rate. Recently, Si nanophotonic waveguide based optical interconnect issue have been comprehensively investigated because of its suitability on integration with Si substrate as compared to other compound semiconductor, which is implemented by replacing Cu bonding wires with sub-micron optical waveguide devices. The optical waveguide is known as the key element to interconnect different devices/modules for the aforementioned purpose. Previously, the Si rib waveguide has been demonstrated [1-6] with its low loss and high index contrast characteristics capable of fabricating many devices, such as optical switches [2], ring resonators [3-5], and small-core waveguides [6]. On the other hand, the Si nanocrystal (Si-nc) has revealed higher radiative recombination rate than bulk Si, which were subsequently employed to develop the active devices such as light emitting diode and waveguide amplifiers [7-9]. In this work, we demonstrate the Si-rich SiO_x strip-loaded waveguide amplifiers with blue-yellow-red amplified-spontaneous-emission (ASE) response by detuning the Si-nc size. By using a strip-loaded waveguide geometry with better lateral confinement than planar waveguide, we utilize the variable strip length (VSL) method to characterize the different gain/loss coefficients and the saturated pumping lengths of these SiO_x:Si-nc based multi-color waveguide amplifiers.

2. EXPERIMENT

The Si-rich SiO_x and stoichiometric SiO_2 films of our waveguides were grown by plasma enhanced chemical vapor deposition (PECVD) at substrate temperature and pressure of 350^oC and 67 Pa, respectively. By changing the fluence ratio of reaction gas and the RF plasma power, the SiO_x layers with changing composition ratio are deposited and the different Si-nc size are detuned after annealing in quartz furnace with N_2 ambient at 1100^oC. The growth parameters and related optical properties are listed in Table 1. The geometry of Si-rich SiO_x strip-loaded waveguide was shown in Fig. 1, in which a 1-um-thick SiO_2 buffer layer was deposited on p-type Si substrate with N_2O/SiH_4 fluence ratio of 20 for 800 sec to prevent optical leakage to substrate. The 0.5-μm-thick Si-rich SiO_x film was deposited upon the SiO_2 buffer layer and the 1-μm-thick top SiO_2 layer was grown to encap the Si-rich SiO_x film for better confinement. Afterwards, the photolithography was performed on the SiO_2 layer to obtain the 5-μm-waide and 3-cm-long waveguide pattern, and the reactive ion etching was used to cleave a 1-μm-deep sharpened side-wall under flowing CHF_3+O_2 gaseous mixture. The strip-loaded waveguide was diced at both ends.

Table 1 The fabrication details and optical properties of Si-rich SiO_2 films prepared by PECVD

	Blue-ASE Sample	Yellow-ASE Sample	Red-ASE Sample
Fluence ratio of $[N_2O]/[SiH_4]$; $[N_2O]$ = 50 sccm	4.5	4.5	4
RF plasma power (W)	50	35	30
Annealing time (minutes)	2.5	90	90
Peak wavelength of PL spectrum (nm)	375	621	801
Linewidth of PL spectrum (nm)	86	189	124
Approximate size of Si-nc (nm)	1.54	2.8	4.7
Refractive index in visible light region	1.56	1.575	1.79

The VSL method shown in Fig. 2 was employed to evaluate the gain and loss coefficients of Si-rich SiO_x

strip-loaded waveguide, in which the circular He-Cd laser beam at 325 nm of 40 mW was reshaped into one-dimension pumping line by using an UV cylindrical lens, which top-illuminates the strip-loaded waveguide with variable pumping length by controlling the slit position back and forth. The amplified spontaneous emission (ASE) signal at the output end of the waveguide was collected by the lens collimated fiber, and analyzed by the monochromator (CVI, DK480) in connection with a photomultiplier tube (Hamamatsu, R5108).

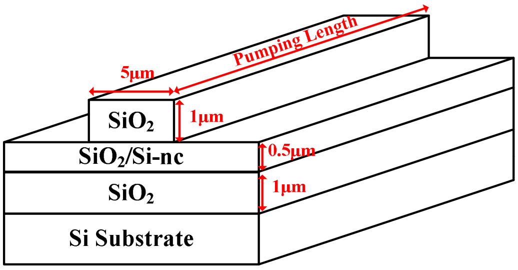

Fig. 1 The geometry structure of Si-rich SiO$_x$ strip-loaded waveguide amplifier.

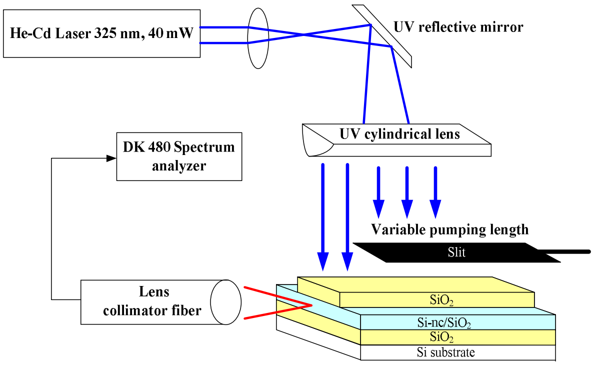

Fig. 2 The experimental setup of VSL method.

3. RESULT AND DISCUSSIONS

The Fig. 3 shows the simulation (R-soft BPM method) of optical propagation in the planar and strip-loaded waveguides with same material structure. The simulated cross section view of optical field for planar and 5-um strip-loaded waveguide clearly shows a well lateral-confined optical mode for the SiO$_x$:Si-nc strip-loaded waveguide due to the tiny effective index difference between air and SiO$_x$. The PL spectra with its intensity normalized to thickness of the Si-rich SiO$_x$ films are shown in Fig. 4. The inset of Fig. 3 shows the PL emission patterns of three samples. The linewidths of these three samples are 86, 189, and 124 nm with peak wavelengths of 375, 621, and 801 nm, and the corresponding sizes of Si-nc are 1.5, 2.8, and 4.7 nm [10]. For the blue- and yellow-ASE samples, the peak PL intensity for blue-ASE samples is twice than yellow-ASE sample. However, the refractive index of blue-ASE sample is smaller than yellow and red ones, which means the blue-ASE sample with lower Si excess than yellow and red ones. Although the lower Si excess in blue-ASE sample, the density of Si-ncs with smaller size of Si-nc in blue-ASE sample is higher than that of with larger size of Si-nc in yellow and red ones. Therefore, the higher density of Si-nc in blue-ASE sample contributes to the higher PL intensity.

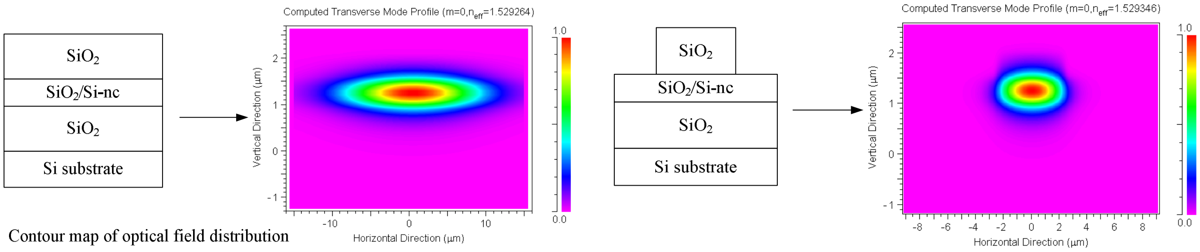

Fig. 3 The simulation of contour map for optical field distribution in planar waveguide and strip-loaded waveguide.

The ASE intensity response versus different pumping length for three 5-um strip-loaded waveguides are shown in Fig. 5, in which the gain and loss of each waveguide amplifier can be fitting with the following equation,

$$I_{ASE} = \frac{I_{spon}}{g-\alpha} * \left(e^{(g-\alpha)z} - 1\right) = \frac{I_{spon}}{-\alpha} * \left(e^{-\alpha z} - 1\right) \text{if g=0}, \tag{1}$$

where g, α, I_{spon}, and z represent the gain, the loss coefficient, the intensity of spontaneous emission, and the pumping length, respectively. As a result, the gain and loss coefficients at peak wavelength of 375 nm for the blue-ASE sample are 160 cm^{-1} and 16 cm^{-1}. For yellow-ASE sample, the gain and loss coefficients at peak wavelength of 620 nm for yellow-ASE sample are 70 cm^{-1} and 15.5 cm^{-1}. For the red-ASE sample with largest size of buried Si-nc, the gain and loss coefficients are determined as 45 cm^{-1} and 14 cm^{-1} at peak wavelength of 780 nm. In addition, the blue-, yellow-, and red-ASE are gradually saturated by lengthening the pumping line with characteristic lengths of 0.18, 0.65, and 1.0 mm. Under He-Cd laser pumping, the spontaneous emission will be amplified when passing through the inversion population region. The ASE intensity increases at larger slope in blue-ASE sample due to the higher population inversion condition developed in the waveguide (also confirmed by the higher PL intensity). That is, the blue-ASE sample with higher PL intensity exhibits higher gain coefficient, whereas the saturation length is smaller for the sample with higher gain coefficient. On the other hand, the dominated scattering loss occurred in the strip-loaded SiO_x:Si-nc waveguide can be attributed to Mie or Rayleigh scattering (Si-nc << λ) at short wavelengths with a proportionality to λ^{-4}. The blue-ASE could experience a stronger Rayleigh scattering in SiO_x with smaller Si-ncs. This essentially elucidates that the loss coefficient of blue-ASE sample is larger than the other samples, as the scattering loss at shorter wavelengths is enhanced by higher density of Si-ncs.

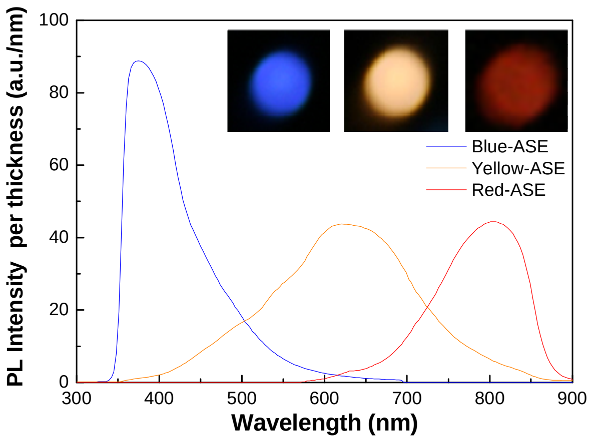

Fig. 4 The spectrum of PL intensity per thickness for three samples. Inset: the PL pattern for three samples.

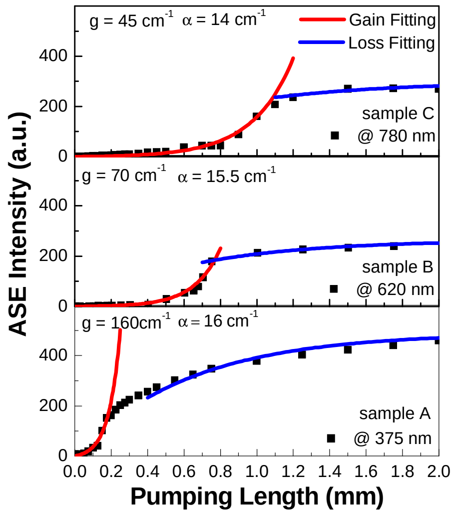

Fig. 5 The ASE intensity versus different pumping lengths for three samples.

4. CONCLUSION

We have characterized the blue-yellow-red multi-color Si-rich SiO_x strip-loaded waveguide amplifiers grown by by PECVD at changing N_2O/SiH_4 fluence ratio and RF plasma power conditions. The PL spectra for blue, yellow, and red samples exhibits peak wavelengths at 375, 621, and 801 nm and corresponding linewidth of 86, 189, and 124 nm. By fitting the VSL experiment data, the maximum gain coefficient of 160 cm^{-1} and saturation length of 0.18 mm are obtained from blue-ASE sample at PL peak of 375 nm, which also exhibits highest loss coefficient of 16 cm^{-1} due to the scattering loss by high density of Si-ncs at shorter wavelength.

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