Efficient and Narrow-Linewidth Photoluminescence Devices Based on Single-Walled Carbon Nanotubes and Silicon Photonics

Supporting Information

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Calculation of *N*: the number of round trips of excitation light in a ring resonator

The photon lifetime in the resonator is given by

$$\tau = \frac{Q}{\omega_0} = \frac{Q}{2\pi c/\lambda_0} \quad , \qquad \text{(S1)}$$

where Q is the resonator Q factor, ω_0 is the resonance angular frequency, c is the speed of light, and λ_0 is the resonance wavelength. If the distance traveled by a photon before it disappears is $\tau c/n$, the number N of round trips is

$$N = \frac{\tau\frac{c}{n}}{D\pi} = \frac{Q\lambda_0}{2\pi^2 Dn} \quad , \qquad \text{(S2)}$$

where n is the equivalent index (effective index) and D is the ring diameter. The constants λ_0 = 1293.5 nm, D = 10 μm, and n = 2.6.[36]

Estimation of the waveguide/resonator coupling loss and the propagation loss by SWNTs

As shown in Fig. 2, the coupling loss between the waveguide and the resonator can be estimated to be 0.36 dB, calculated from the depth (~ 11 dB) of resonance dip of Fig. 2(c) (i.e., the coupling efficiency between the waveguide and the resonator can be roughly estimated to be 92%). This very-low-coupling loss of 0.36 dB can be negligible in the calculation of a PL enhancement factor *F*. In addition, from the *Q* factors before cladding, before and after deposition of SWNTs shown in Fig. 2(d), 2(e) and 2(f), respectively, the propagation loss of waveguide deposited SWNTs can be estimated taking into account the window width (10 μm) in Fig. 1(a). The estimated propagation loss of waveguide deposited SWNTs is 9.16 dB/cm. That is, from the coupling loss of 0.36 dB and the propagation loss of 0.27 dB by waveguide deposited SWNTs of *L* = ~300 μm [obtained from Fig. 4(a)], ~86% of the input light can be injected into the ring resonator, indicating that these loss can be negligible in the calculation of a PL enhancement factor *F*.

Methods of photoresist cladding and the window for depositing SWNTs

After the fabrication of the silicon waveguide and the micro-resonator on silicon-on-insulator substrates, ZPN1150 photoresist is spin-coated at 3000 rpm and baked at 110° C for 2 minutes. The window in the photoresist was formed by photolithography and Tetramethylammonium hydroxide (TMAH) developer.

Images of scanning electron microscope of resonators after depositing SWNTs

Figures S1a and S1b show the scanning electron microscope images of ring and disk resonators with photoresist cladding after depositing SWNTs, respectively.

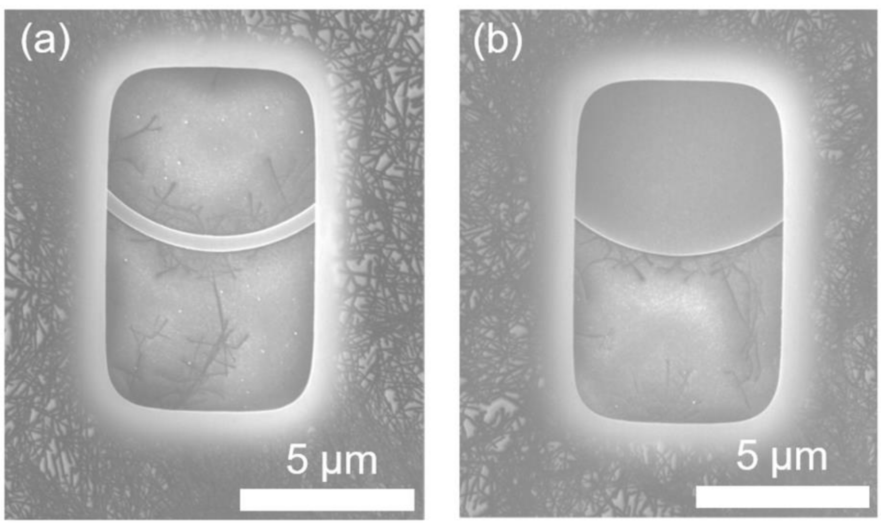

Figure S1. Scanning electron microscope images of (a) ring and (b) disk resonator with photoresist cladding and SWNTs. The ring and disk resonator were 10 μm in diameter.

Transmission spectrum of device with ring resonator in O band and the mechanism of the PL enhancement

In order to discuss the mechanism of the PL enhancement with a factor F of 34, we estimated the Q factor from Eq. (3) in the main text. Assuming that the number N corresponds to the PL enhancement factor of 34, then the Q factor is estimated to be 13,500. Figure S2 shows the experimental transmission spectra of 10-μm-diameter ring resonator in O band after deposition of SWNTs (red curve). From the fitting with Lorentzian function, the Q factor is roughly estimated to be ~15,000, which is in good accordance with the Q factor of 13,500 estimated from Eq. (3). We note that the Q factor in O band (~15,000) is higher than that in C and L bands (~4,000 shown in Fig. 2f). This is because the optical coupling between the resonator and SWNTs in O band is lower than that in C and L bands owing to the lower evanescent field in the short wavelength range.

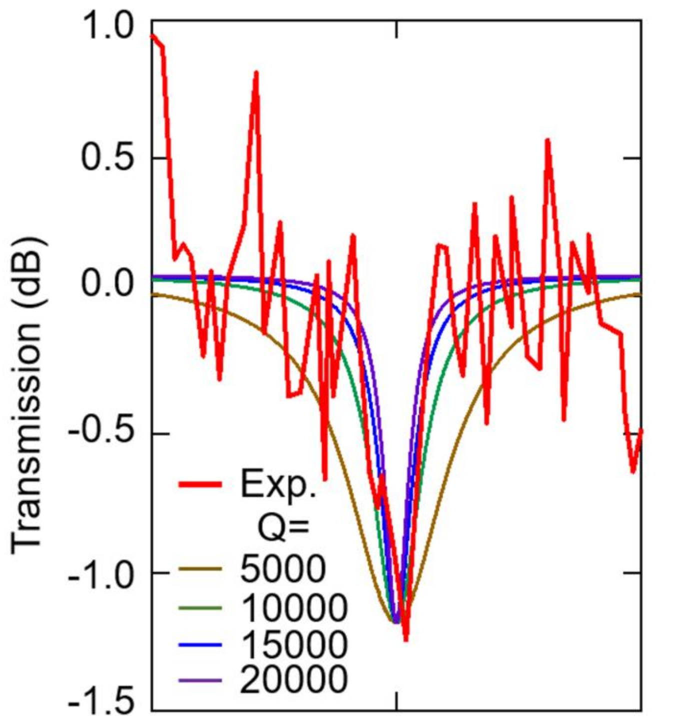

Figure S2. Experimental transmission spectrum of 10-μm-diameter ring resonator in O band after deposition of SWNTs (red curve). Brown, green, blue and purple curves are fits to Lorentzians that give the Q factors shown in the legends. We note that the wavelength resolution and the stability of the experimental transmission spectrum is low because the O-band tunable laser in this study is stepping-tunable laser, which is different from the swept-tunable laser used in C and L bands.

Transmission spectra of device with disk resonator in C and L bands

Figures S3a–S3c show the transmission spectra of the device with a disk resonator before and after cladding with photoresist and after depositing SWNTs, respectively. In contrast with the single mode of the ring resonator, the disk resonator has three optical modes.[45] The *Q* factors are 47767 (8357) before (after) cladding deposition, as shown in Fig. S3d (Fig. S3e). This decrease in the *Q* factor is caused by increased coupling between the ring resonator and the waveguide due to photoresist filling in the air gap between the two. After depositing SWNTs (Fig. S3f), the *Q* factor decreases to 7921 due to absorption and scattering loss by the deposited SWNTs.

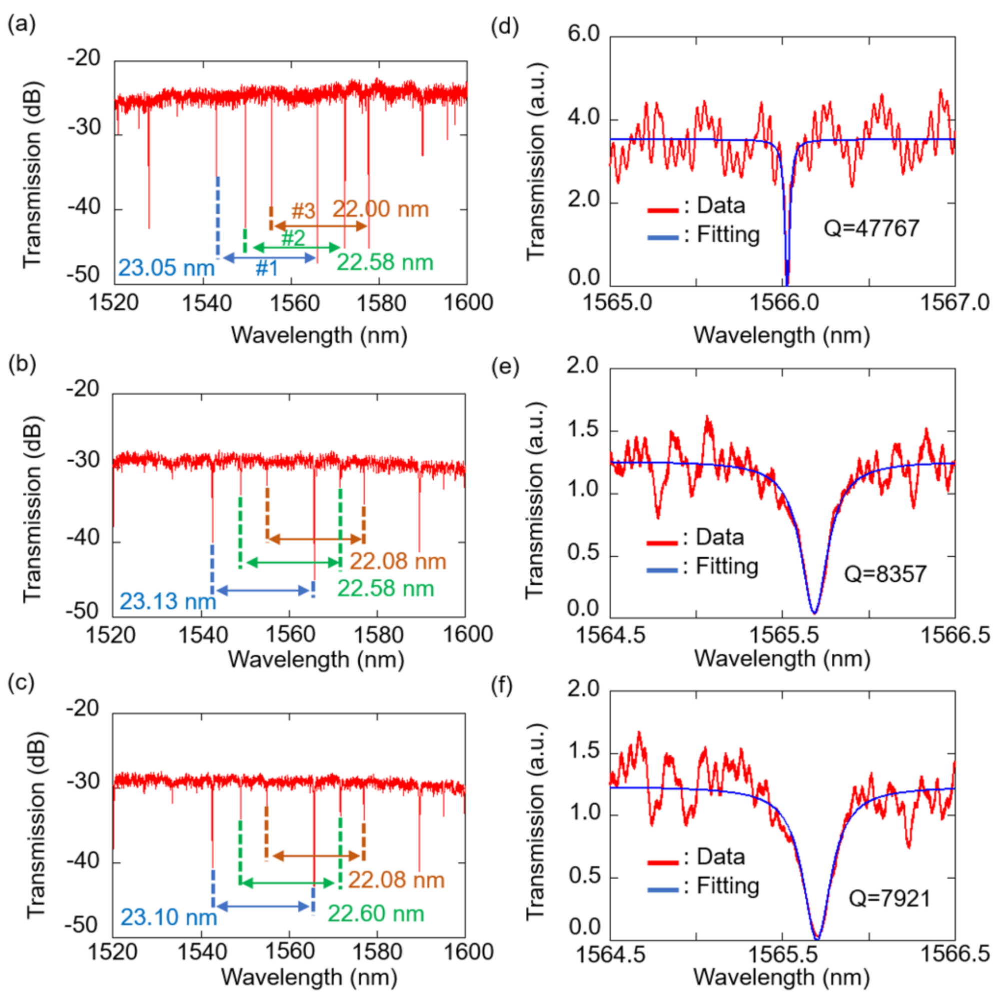

Figure S3. Transmission spectra of 10-μm-diameter disk resonator in C and L bands (a) before photoresist cladding, (b) after cladding, and (c) after deposition of SWNTs. The FSRs are shown in the figures. (d-f) Expanded spectra (red curves) of the resonant transmission peaks from panels (a)–(c) on a linear scale. The transmission spectra were measured with 1-mW input light. Blue curves are fits to Lorentzians that give the *Q* factors shown in the legends.

O-band transmission spectra of device with disk resonator

Figure S4 shows the transmission spectrum of the disk resonator after depositing SWNTs in the O band. The transmission dip appears at the resonance wavelength (1319.6 nm). At this excitation wavelength, the excitation light confined in the disk resonator can be observed by using the NIR camera (see Fig. 5d in the main text). This wavelength was used for the resonant excitation.

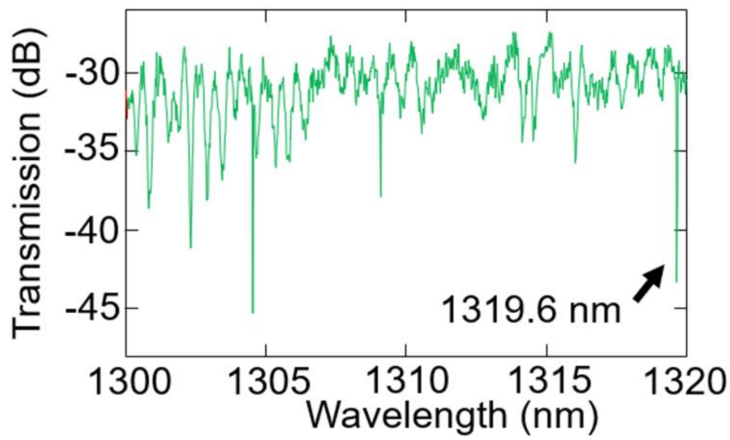

Figure S4. Transmission spectrum of disk resonator in O band after depositing SWNTs.

Group index n_g and *Q* factors of ring and disk resonators

Based on the transmission measurements shown in Figs. 2 and S2, we estimate the group index n_g and *Q* factors of the ring and disk resonators before and after cladding with photoresist and after depositing SWNTs. The ring resonator is more sensitive to cladding because it has both inner and outer sidewalls. Therefore, the ring resonator has a larger group index than the disk resonator due to the photoresist and the large decrease in the group refractive index.[36,37] The photoresist cladding reduces the *Q* factor by 63.8% for the ring resonator and 82.5% for the disk resonator. The reduced *Q* factor is caused by increased coupling between the resonator and the linear waveguide, which is due to photoresist filling into the air gap between the two. Upon deposition of SWNTs, the *Q* factor decreases by 19.5% for the ring resonator and 5.2% for the disk resonator. Since the ring resonator has both inner and outer sidewalls, deposition of SWNTs leads to large loss, so the *Q* factor decreases more than for the disk resonator.

Table S1. Group index and *Q* factor before and after cladding with ZPN 1150 photoresist and after deposition of SWNTs.

	Ring resonator				Disk resonator			
	n_g	Diff. n_g (%)	*Q*	Diff. *Q* (%)	n_g	Diff. n_g (%)	*Q*	Diff. *Q* (%)
Before cladding	4.64		14227		3.34		47767	
After cladding	4.32	-6.9	5144	-63.8	3.32	-0.6	8357	-82.5
After depositing SWNTs	4.28	-0.9	4141	-19.5	3.32	-0.0	7921	-5.2