Research article

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Diffraction engineering for silicon waveguide grating antenna by harnessing bound state in the continuum

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Abstract: Silicon waveguide grating antennas (SWGAs) have been widely employed to interface the guided and radiation modes in various integrated photonic systems. However, ultrasmall feature sizes or heteromaterial integrations are usually required to obtain long propagation length and small far-field divergence. Moreover, for conventional SWGAs, the diffraction strength is wavelength sensitive, so the output power and far-field divergence will deviate in the beam steering process. In this paper, we propose and demonstrate a novel approach to engineer the diffraction in SWGA by harnessing the bound state in the continuum (BIC). A new degree of freedom is attained in diffraction engineering by introducing the “modified” diffraction formula. The side-wall emission can be dramatically depressed by building the quasi-BIC at critical waveguide width, leading to ultrauniform diffraction. The extremely weak diffraction strength ($\sim 3.3 \times 10^{-3}$ dB/ μm) has been experimentally realized for the fabricated device with a large feature size (~ 60 nm). From the measurement results, one can predict a centimeter-scale propagation length and an ultrasmall divergence ($\sim 0.027^\circ$). Moreover, the diffraction strength dispersion can be flattened for SWGA with critical waveguide width. Such effect has also been experimentally verified. Our proposed design is the first one that introduces the BIC effect into SWGA optimization, paving the way for precise diffraction engineering and high-performance integrated optical antennas.

1 Introduction

A silicon (Si) waveguide grating antenna (SWGA) is an Si-on-insulator (SOI) waveguide with periodic grating structures that diffract the guided mode into the radiation mode. SWGAs have been widely applied in various photonic integrated systems, e.g. light detection and ranging (LiDAR) [1–3], high-resolution microscopy [4], biophotonic probing [5], and low-cost biosensors [6, 7]. The spatial resolution is critical for all these applications, so the small far-field divergence is desired for SWGA. However, the input light can only propagate over a short distance (less than a few hundred micrometers) in conventional SWGAs due to the significant diffraction strength, leading to the relatively large far-field divergence. In SWGA, the conventional diffraction formula can be written as [8]

$$\kappa = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}} \Lambda_{\text{grt}}} \quad (1)$$

where κ is the coupling coefficient, Δn_{eff} is the index perturbation caused by the grating structures, n_{eff} is the effective index of the guided mode, and Λ_{grt} is the grating pitch. Thus, one has to reduce the index perturbation to achieve weak diffraction. One possible solution is to reduce the corrugation of the grating structures, e.g. SWGA with a 10 nm feature size can provide 1 mm propagation length [9]. However, it is quite challenging to realize such a small feature size considering the current state of fabrication technology. An alternative is to combine the high-index Si waveguide with the low-index Si-nitride overlay [8, 10, 11]. However, such Si/Si-nitride hybrid platform requires additional deposition and etching steps, leading to the complex fabrication process. Furthermore, for SWGA-based systems, the beam steering process is commonly

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required to scan the surrounding environment and locate the receivers [3, 12]. The SWGA diffraction angle can be steered by tuning the working wavelength. However, the diffraction strength is wavelength sensitive for conventional SWGAs, so the output power and far-field divergence will deviate in the beam steering process, which makes the scanning operation unstable.

The photonic bound state in the continuum (BIC) is a lossless nonradiating state localized within the continuum spectrum of the radiation mode [13, 14]. In practice, the ideal BIC will transform into quasi-BIC due to material absorption, surface roughness, fabrication imperfection, substrate leakage, or other perturbations [15]. Quasi-BICs can be realized on various platforms, e.g. photonic crystals [16], asymmetric metasurfaces [17], dual-grating membranes [18], fiber Bragg gratings [19], and low-contrast waveguides [20, 21]. In this paper, the novel concept of BIC is introduced to engineer the diffraction in SWGA. A new degree of freedom is attained in diffraction engineering by introducing the “modified” diffraction formula. The proposed structure is an Si waveguide with periodic nanogrooves on the side walls. The diffraction strength can be dramatically depressed even with a large feature size

by tailoring the intrawaveguide interference. Such interference effect also induces a flattened dispersion curve for the diffraction strength. Moreover, the proposed BIC-based SWGA is designed on the all-Si platform without heteromaterial integrations, leading to an easy fabrication process. One might find that some similar SWGAs with side-wall corrugations have been demonstrated in LiDAR systems [1, 9]. However, these reported structures still suffer from the significant diffraction strength and short propagation length, as they are all designed based on the conventional diffraction formula and the BIC nature has not been revealed. Our proposed design is the first one that introduces the BIC effect into SWGA optimization, paving the way for precise diffraction engineering and high-performance integrated optical antennas.

2 Design and principle

Figure 1A and B shows the schematics for the proposed SWGA, which is an Si waveguide with periodic nanogrooves on the side walls. The device is designed based

Figure 1: Working principle for BIC-based SWGA.

(A) 3D view of SWGA. (B) Enlarged top view of SWGA with some key parameters labeled. (C) Schematics for the BIC effect in SWGA. The bound state is the TE_0 mode that propagates along the Si waveguide (toward the $+x$ -direction), whereas the continuum is the radiation mode that propagates in free space. In SWGA, the nanogrooves diffract the confined TE_0 mode into the radiation mode $[E_{L(-)}$ and $E_{R(+)}]$. One should note that nanogrooves also excite the scattering modes $[E_{L(+)}$ and $E_{R(-)}]$ confined within the Si core region, so the side-wall emission in SWGA can be dramatically depressed by building a destructive intrawaveguide interference between $E_{L(+)}$ and $E_{R(-)}$. Thus, only a small part of light can emit from the top and bottom surfaces (E_T and E_B), leading to limited diffraction with an ultrasmall far-field divergence.

on the SOI platform with an Si core layer ($n_{\text{Si}}=3.46$, $h_{\text{Si}}=250$ nm) and an SiO_2 buffer layer ($n_{\text{SiO}_2}=1.45$, $h_{\text{SiO}_2}=3$ μm). The cladding is chosen to be a PMMA polymer layer ($n_{\text{PMMA}}=1.50$, $h_{\text{PMMA}}=500$ nm) [22–26]. In this paper, we only consider the transverse-electric (TE) polarization. For such a structure, the bound state is the fundamental TE mode (TE_0) that propagates along the Si waveguide (toward the $+x$ -direction), whereas the continuum is the radiation mode that propagates in free space. In SWGA, the incident TE_0 mode can be coupled into the radiation mode [$E_{\text{L}(-)}$ and $E_{\text{R}(+)}$] by nanogrooves. It should be noted that nanogrooves also excite the scattering modes [$E_{\text{L}(+)}$ and $E_{\text{R}(-)}$] confined within the Si core region (see also Supplementary Material, Section 1). Hence, the side-wall emission can be dramatically depressed by building a destructive intrawaveguide interference between $E_{\text{L}(\pm)}$ and $E_{\text{R}(\pm)}$, leading to diffraction-limited quasi-BIC [20], as shown in Figure 1C. It should be noted that such phenomenon is induced by the “accidental” BIC effect [14], which emerges by introducing the interference between different diffraction channels while preserving the structural symmetries. A “modified” diffraction formula is obtained to describe the BIC effect by inserting an interference term into Eq. (1) [20, 21]:

$$\kappa = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}} \Lambda_{\text{grt}}} \left| \frac{1}{2} + \frac{1}{2} \exp \left\{ i \left[\frac{2n_s \pi (w_{\text{wg}} - 2r_{\text{grt}})}{\lambda_0} + \varphi_0 \right] \right\} \right| \quad (2)$$

where κ is the “modified” coupling coefficient, n_s is the effective index of $E_{\text{L}(+)}$ and $E_{\text{R}(-)}$, w_{wg} is the waveguide width, r_{grt} is the nanogroove radius, λ_0 is the working wavelength, and φ_0 is the intrinsic phase difference between $E_{\text{L}(\pm)}$ and $E_{\text{R}(\pm)}$. For the conventional diffraction formula [see Eq. (1)], the diffraction strength is solely determined by the index perturbation. For the “modified” diffraction formula [see Eq. (2)], a new degree of freedom is introduced to engineer the diffraction by exploiting the intrawaveguide interference. From Eq. (2), the diffraction-limited quasi-BICs can be built at some critical waveguide widths w_c :

$$w_c = \frac{[(2m+1)\pi - \varphi]\lambda_0}{2n_s\pi} + 2r_{\text{grt}} \quad (m=1, 2, 3 \dots) \quad (3)$$

Such interference effect has also been observed in other BIC-based platforms such as dual-grating membranes [18] and low-contrast waveguides [20, 21]. However, a small part of light can still emit from the top and bottom surfaces (E_{T} and E_{B}) even at critical waveguide width $w_{\text{wg}}=w_c$, as

the top/bottom emission is not forbidden (see Figure 1C). Thus, the rigorous diffraction formula can be written as

$$\kappa = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}} \Lambda_{\text{grt}}} \left| \frac{1+\Gamma}{2} + \frac{1-\Gamma}{2} \exp \left\{ i \left[\frac{2n_s \pi (w_{\text{wg}} - 2r_{\text{grt}})}{\lambda_0} + \varphi_0 \right] \right\} \right| \quad (0 < \Gamma < 1) \quad (4)$$

where Γ is a parameter quantifying the incomplete diffraction elimination. The intrinsic phase difference is $\varphi = \pi$ for SWGA with a symmetric geometry [18, 21]. As an initial setting, the nanogroove radius is chosen to be $r_{\text{grt}} = 60$ nm. The working wavelength is set to be $\lambda_0 = 1.55$ μm . It should be noted that $E_{\text{L}(+)}$ and $E_{\text{R}(-)}$ can be roughly approximated as the slab modes with confinement only in the z -dimension (see also Supplementary Material, Section 1). The effective index is then calculated to be $n_s = 2.95$ for $E_{\text{L}(+)}$ and $E_{\text{R}(-)}$ using the finite element method. According to Eq. (3), the critical waveguide width is calculated to be $w_{c,m} = 0.64 + 0.52m$ μm for the m th-order quasi-BIC.

The diffraction angle θ_d for SWGA can be determined by the following equation:

$$\sin \theta_d = n_{\text{eff}} - \frac{\lambda_0}{\Lambda_{\text{grt}}} \quad (5)$$

where n_{eff} is the effective index of the TE_0 mode, λ_0 is the working wavelength, and Λ_{grt} is the grating pitch. The grating pitch is then chosen to be $\Lambda_{\text{grt}} = 700$ nm with the corresponding $\theta_d \approx 25^\circ$ at the 1.55 μm wavelength. To verify the BIC effect, we then calculate the diffraction strength for SWGA with varied w_{wg} , as shown in Figure 2A. Here, the diffraction strength α is defined as

$$\alpha = \frac{-10 \log_{10}(1-S)}{l_{\text{grt}}} \quad (6)$$

where S is the radiation power and l_{grt} is the propagation length. Here, the SiO_2 buffer layer thickness h_{SiO_2} is assumed to be infinite. The numerical calculation is carried out using the 3D finite-difference time-domain method. More simulation details can be found in Supplementary Material, Section 2. According to the conventional diffraction formula [see Eq. (1)], α should monotonously decrease with the increasing w_{wg} , as the index perturbation is weaker with a larger w_{wg} . However, it can be seen in Figure 2A that α periodically reaches a minimum value, which indicates the diffraction depression induced by the BIC effect. Similar phenomena have also been observed in other BIC-based photonic systems [18, 20, 21]. Critical waveguide widths are calculated to be $w_{c,1} = 600$ nm, $w_{c,2} = 1.14$ μm , and $w_{c,3} = 1.68$ μm for the

Figure 2: Diffraction properties for BIC-based SWGA.

Calculated (A) linear-scale and (B) logarithmic-scale diffraction strength α with varied waveguide width w_{wg} at the 1.55 μm wavelength. The diffraction strength periodically reaches a minimum value at some critical waveguide widths $w_{\text{c},i}$, which is mainly due to the BIC effect. The first critical waveguide width is calculated to be $w_{\text{c},1} = 600$ nm. (C) Calculated α spectra with varied w_{wg} . The dot markers denote the zero-dispersion wavelengths. For the BIC-based SWGA with $w_{\text{wg}} = w_{\text{c},1}$, the interference-induced zero dispersion can be obtained at the central wavelength, leading to a flattened dispersion curve. (D) Calculated α spectra with varied nanogroove radius r_{grt} .

first three quasi-BICs (qBIC₁, qBIC₂, and qBIC₃), which show great agreement with the analytical model [see Eq. (3)]. Here, qBIC_{*m*} denotes the *m*th-order quasi-BIC. Figure 2B shows the calculated α using a logarithmic scale. It can be observed in Figure 2B that the diffraction is not fully eliminated for quasi-BICs, which is mainly due to the top/bottom emission. The diffraction strength is calculated to be $\alpha_1 = 2.0 \times 10^{-3}$ dB/ μm , $\alpha_2 = 6.0 \times 10^{-4}$ dB/ μm , and $\alpha_3 = 1.7 \times 10^{-4}$ dB/ μm for qBIC₁, qBIC₂, and qBIC₃, respectively. One can find that α can be reduced further for higher-order quasi-BICs. However, the relatively small w_{wg} is usually required to obtain the relatively high group index n_g and ensure an efficient beam steering (see Supplementary Material, Section 3). Thus, the waveguide width is chosen to be $w_{\text{wg}} = 600$ nm to ensure a weak diffraction as well as a high beam steering efficiency.

We then calculate the α dispersion curves for BIC-based SWGAs, as shown in Figure 2C. For SWGA with $w_{\text{wg}} = 600$ nm = $w_{\text{c},1}$, the zero dispersion ($\partial\alpha/\partial\lambda = 0$) can be obtained at the central wavelength, leading to a flattened dispersion curve with $\Delta\alpha < 1.0 \times 10^{-3}$ dB/ μm over the 100 nm wavelength range from 1.5 to 1.6 μm . We also calculate the

α dispersion curves for SWGAs with $w_{\text{wg}} = 580$ nm $< w_{\text{c},1}$ and $w_{\text{wg}} = 620$ nm $> w_{\text{c},1}$, as shown in Figure 2C. One can find that the dispersion flattening can still be achieved, but the zero-dispersion wavelength is slightly shifted. Such dispersion flattening is mainly induced by the interference effect. The destructive interference condition can be perfectly satisfied only at the central wavelength, so the wavelength deviation will introduce the phase mismatch between $E_{\text{L}(\pm)}$ and $E_{\text{R}(\pm)}$, leading to the negative α dispersion ($\partial\alpha/\partial\lambda < 0$) when $\lambda < \lambda_0$ and the positive α dispersion ($\partial\alpha/\partial\lambda > 0$) when $\lambda > \lambda_0$. As a comparison, we also calculate the α dispersion curve for the conventional SWGA with shallowly etched nanoholes on the top surface (see Supplementary Material, Section 4). The diffraction strength is calculated to be $\alpha = 7.8 \times 10^{-2}$ dB/ μm for conventional SWGAs, which is much higher than the calculation result for the BIC-based SWGA. One can also find that the α dispersion is always positive for conventional SWGAs, which is mainly due to the weaker light confinement and the stronger disturbance at the longer wavelength. We then calculate the α dispersion curves with varied r_{grt} , as shown in Figure 2D. It can be found that α can be further reduced by choosing an even smaller r_{grt} . The diffraction strength is calculated to be $\alpha = 4.3 \times 10^{-4}$ dB/ μm for the BIC-based SWGA with $r_{\text{grt}} = 40$ nm. Moreover, dispersion flattening can still be maintained with varied r_{grt} . However, the smaller feature size will give rise to fabrication difficulties. Thus, the nanogroove radius is finally chosen to be $r_{\text{grt}} = 60$ nm to obtain a weak diffraction as well as an easy fabrication process.

The optimized parameters are summarized as follows: $w_{\text{wg}} = 600$ nm, $\Lambda_{\text{grt}} = 700$ nm, $r_{\text{grt}} = 60$ nm, and $h_{\text{Si}} = 250$ nm. The light propagation profiles are then calculated for the optimized SWGA, as shown in Figure 3A and B. It can be observed that the incident TE₀ mode can be coupled into the radiation mode by nanogrooves (see Figure 3A). Moreover, for the BIC-based SWGA, the side-wall emission is depressed, whereas the top/bottom emission is dominant (see Figure 3B). As a comparison, we also calculate the light propagation profiles with $w_{\text{wg}} = 800$ nm $> w_{\text{c},1}$, as shown in Figure 3C and D. One can observe that the light emits from both side walls and top/bottom surfaces, leading to a much stronger diffraction. We also calculate the element factor for the BIC-based SWGA [27], as shown in Supplementary Material, Section 5. It can be found that the far-field pattern is azimuthally uniform for SWGA with $w_{\text{wg}} = 600$ nm = $w_{\text{c},1}$ at different wavelengths. For the above analysis, the SiO₂ buffer layer thickness h_{SiO_2} is assumed to be infinite. However, there is usually an Si substrate buried under the SiO₂ buffer layer [28], which will reflect a small part of the radiation mode and slightly affect the

Figure 3: Calculated light propagation profiles ($|E_y|$ field) for BIC-based SWGAs with (A and B) $w_{wg} = 600 \text{ nm} = w_{c,1}$ and (C and D) $w_{wg} = 800 \text{ nm} > w_{c,1}$. The logarithmic scale is used to enhance the contrast. For SWGA with $w_{wg} = w_{c,1}$, the side-wall emission is depressed, whereas the top/bottom emission is dominant. For SWGA with $w_{wg} > w_{c,1}$, the light emits from both side walls and top/bottom surfaces.

diffraction (see Supplementary Material, Section 6). The diffraction strength is calculated to be $\alpha = 2.1 \times 10^{-3} \text{ dB}/\mu\text{m}$ for the optimized SWGA on the commercial SOI platform with $h_{\text{SiO}_2} = 3 \mu\text{m}$, which is quite close to the calculation result for SWGA with infinite h_{SiO_2} , indicating a weak bottom reflection.

3 Fabrication and characterization

To verify the above analysis, we fabricated the BIC-based SWGAs on the 250 nm SOI platform (SOITEC, Inc.). The SOI chip was first spin-coated with the positive-tone electron-beam resist (PMMA) and prebaked at 180°C for 10 min. An electron beam lithography (Raith 150-II) process with the exposure dose of $300 \mu\text{C}/\text{cm}^2$ was performed to define the pattern. The Si core layer was then fully etched by implementing an inductively coupled plasma reactive ion etching process with a gas mixture of C_4F_8 and SF_6 . Another overlay exposure with PMMA resist followed by a 50 nm shallow etching was performed to fabricate the TE-type grating couplers for the fiber-chip coupling

and polarization selectivity [28]. Finally, the whole chip was spin coated with a 500-nm-thick PMMA layer as the cladding.

To observe the BIC effect, one possible solution is to characterize the far-field pattern. However, for the optimized SWGA, the centimeter-scale propagation length is required to obtain $>99\%$ power efficiency ($l_{20 \text{ dB}} = 20 \text{ dB}/\alpha \approx 1 \text{ cm}$), leading to an extremely small far-field divergence $<0.02^\circ$. Although the Fourier imaging system with a high resolution $<0.01^\circ$ has been developed in Ref. [3] to characterize the optical antenna, it is still quite challenging to measure the far-field pattern with such a small divergence, as the main lobe can only occupy a few pixels [11]. To directly demonstrate the BIC effect, we measured the diffraction strength for fabricated SWGAs. A series of SWGAs with varied l_{grt} (from 400 to 2000 μm) were fabricated to evaluate α , as shown in Figure 4A. The Si waveguides without nanogrooves were also fabricated on the same chip for normalization. Figure 4B and C shows the scanning electron microscopy (SEM) image for fabricated SWGA and Si waveguide. The tunable laser (Agilent 81600B) was used to excite the TE_0 mode at the input ports ($i_1, i_2, \dots, i_{10}$). The power meter (Agilent 81635) was used to detect the transmission responses at the output ports ($o_1, o_2, \dots, o_{10}$). Figure 5A shows the measured excess losses for fabricated SWGAs with $w_{wg} = 600 \text{ nm}$ and varied l_{grt} at the $1.55 \mu\text{m}$ wavelength. Here, the excess loss is defined as

$$\text{EL} = -10 \log_{10} \left(\frac{T_{\text{SWGA}}}{T_{\text{wg}}} \right) \quad (7)$$

where EL is the excess loss, T_{SWGA} is the measured transmittance for SWGA, and T_{wg} is the transmittance for the Si waveguide. By linearly fitting the measured excess losses, the diffraction strength was characterized to be $\alpha \approx 3.3 \times 10^{-3} \text{ dB}/\mu\text{m}$, which agrees well with the simulation result. SWGAs with varied w_{wg} were also fabricated on the same chip to demonstrate the BIC effect. Figure 5B shows the measured α with varied w_{wg} at the $1.55 \mu\text{m}$ wavelength. It can be seen that the measured α reaches a minimum value at critical waveguide width $w_c \approx 600 \text{ nm}$, indicating the diffraction-limited qBIC₁. The α dispersion was also measured for fabricated SWGA with $w_{wg} = 600 \text{ nm}$ to verify the dispersion flattening effect, as shown in Figure 6C. From the measurement results, one can observe a flattened dispersion curve with zero dispersion around the $1.55 \mu\text{m}$ wavelength. To further demonstrate the BIC effect, we also fabricated some shallow-ridge tapers to characterize the side-wall emission of fabricated SWGAs (see Supplementary Material, Section 7), as shown in Figure 4D. Each shallow-ridge taper can collect the

Figure 4: The fabricated SWGAs.

(A) Optical microscopy image for fabricated Si waveguides and SWGAs with varied propagation length l_{grt} . SEM images for fabricated (B) Si waveguide and (C) SWGA. (D) Enlarged optical microscopy image for the fabricated shallow-ridge taper.

Figure 5: Measurement results for fabricated SWGAs.

(A) Measured excess losses (ELs) for fabricated SWGAs with $w_{wg} = 600$ nm and varied l_{grt} at the 1.55 μm wavelength. The red dashed line shows the linear fitting. The diffraction strength was measured to be $\alpha \approx 3.3 \times 10^{-3}$ dB/ μm . (B) Measured α for fabricated SWGAs with varied w_{wg} at the 1.55 μm wavelength. The qBIC₁ can be found at $w_{wg} \approx 600$ nm. (C) Measured α for fabricated SWGAs with $w_{wg} = 600$ nm at different wavelengths. The error bars refer to the standard errors of the linear fittings. The gray dashed lines show the simulation results. (D) Measured transmittances at the O'_i ports for fabricated SWGAs with $w_{wg} = 600$ nm = $w_{c,1}$ and $w_{wg} = 800$ nm $>$ $w_{c,1}$. The gray dashed line shows the detection limit (DL). The red and blue dashed lines show the linear fittings.

side-wall emission over a 50 μm propagation length. The spacing between the adjacent shallow-ridge taper is 200 μm . The TE₀ mode was launched at the i_0 input port using

Figure 6: Predicted far-field intensities for fabricated SWGAs with varied w_{wg} and l_{grt} according to the measured α at the 1.55 μm wavelength.

the tunable laser, whereas the collected side-wall emission was detected at the output ports ($O'_1, O'_2, \dots, O'_{10}$) using the power meter, as shown in Figure 4A. Figure 5D shows the measured transmittances at the O'_i ports for fabricated SWGAs with $w_{wg} = 600$ nm and $w_{wg} = 800$ nm. For fabricated SWGA with $w_{wg} = 600$ nm = $w_{c,1}$, the side-wall emission is both weak and uniform, indicating the diffraction depression effect induced by the quasi-BIC. In contrast, for fabricated SWGA with $w_{wg} = 800$ nm $>$ $w_{c,1}$, the side-wall emission decays rapidly over a short distance, indicating the significant diffraction strength. To further evaluate the performance of fabricated SWGAs, we also predict the divergence angles $\delta\theta_{3dB}$ by calculating the far-field intensities according to the measured α , as shown in Figure 6.

The calculation details for the near-to-far transform can be found in Ref. [11]. For SWGA with $w_{\text{wg}} = 600 \text{ nm} = w_{\text{c},1}$, the divergence angle decreases as the truncated propagation length varies from $l_{\text{grt}} = 0.5$ to 10 mm . An extremely small divergence angle $\delta\theta_{3\text{ dB}} \approx 0.027^\circ$ can be predicted for SWGA with $l_{\text{grt}} = 10 \text{ mm}$, indicating ultrauniform diffraction. In contrast, for SWGA with $w_{\text{wg}} = 800 \text{ nm} > w_{\text{c},1}$, the divergence angle keeps nearly constant as the truncated propagation length varies from $l_{\text{grt}} = 0.5$ to 10 mm , indicating that most of the input power has been diffracted over a short propagation length. Such rapid power decay also leads to a relatively large divergence angle $\delta\theta_{3\text{ dB}} \approx 0.25^\circ$.

4 Conclusion and discussion

In conclusion, we propose and demonstrate a novel approach to engineer the diffraction in SWGAs by exploiting the BIC effect. The diffraction strength can be tailored using intrawaveguide interference. The side-wall emission can be dramatically depressed by building quasi-BICs at some critical waveguide widths, leading to the weak and uniform diffraction process. The extremely weak diffraction strength ($\sim 3.3 \times 10^{-3} \text{ dB}/\mu\text{m}$) has been experimentally demonstrated for the fabricated device with a large feature size ($\sim 60 \text{ nm}$). An ultralong propagation length $l_{\text{grt}} > 1 \text{ cm}$ and an ultrasmall far-field divergence $\sim 0.027^\circ$ can be predicted from the measurement results. Moreover, the diffraction strength dispersion can be flattened for SWGA at critical waveguide width, which is also induced by the BIC effect. Zero dispersion has been experimentally observed for the fabricated BIC-based SGWA. The BIC-based SWGA is designed based on the all-Si platform, so the device can be easily realized using the CMOS-compatible fabrication technology. Moreover, such novel BIC effect can also be used to engineer the diffraction strength for the silicon-nitride antenna at visible wavelengths [29], as shown in Supplementary Material, Section 8. Our proposed design is the first one that introduces the BIC effect into SWGA optimization, paving the way for precise diffraction engineering and high-performance integrated optical antennas.

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