# Broadband and Low-Loss Metamaterial Silicon Nitride Edge Coupler

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**Abstract:** We report a SiN edge coupler based on metamaterial structure with simple fabrication process, the coupling loss with SMF is 1.60/2.21 dB at 1310/1550 nm. The loss is smaller than 1.86/2.80 dB in O/S+C+L band.

## 1. Introduction

With the rapid emergence of new technologies such as 5G communications, cloud computing, autonomous driving and telemedicine, humanity has entered the era of "digitalization" and "big data". Faced with an increasing amount of data, the traditional microelectronic chips based on electrical interconnection encounter bottlenecks in terms of speed, bandwidth and energy consumption. Silicon (Si)-based integrated photonic chip is one of the key technologies to break through this dilemma. Due to the low loss, large bandwidth, high integration density and compatible with CMOS process, Si photonics (SiPh) is attracting more and more attention and research. Silicon nitride (SiN) has the superiority in terms of extremely low propagation loss, wide working bandwidth and high nonlinearity [1], and has been the momentous material for SiPh devices. Moreover, through hybrid integration and heterogeneous integration, SiN materials can be integrated with Si, III-V materials or lithium niobate materials on the same chip, breaking through the limitation that SiN can only be used as a passive device [2]. However, achieving the high-efficiency optical interconnection between SiN waveguide and optical fiber has always been a challenge.

Currently, off-plane grating coupling and in-plane edge coupling are the popular strategies to realize the optical coupling between fiber and SiPh chip [3]. The grating coupling is a common solution at the stage of chip test, but the narrow bandwidth, high loss and polarization dependence produced by the inherent diffractive characteristics will cause the performance deterioration in transmission system. Relatively, edge coupler provides alternative principle of mode field size matching between fiber and SiPh chip, thus can improve bandwidth, coupling loss and polarization dependence fundamentally. Using the high-cost lens fiber with small fiber mode field (less than 3 μm), the ultra-low loss (smaller than 1 dB) edge coupling can be realized [4,5]. But the high requirement of alignment between lens fiber and coupler arises the limitation in practical application. Therefore, realizing low-loss light coupling between a standard single-mode fiber (SMF) and SiPh chip is strongly desired for industry, especially for optical module.

Recent years, metamaterial SiPh structures have drawn momentous attention during the evolution of highly compact and ultra-low loss edge couplers. Particularly, due to the excellent optical properties and CMOS compatible process, SiN has been a widely employed material choice [6]. The coupling efficiency can be obviously increased by utilizing the SiN metamaterial structures with suspended and multi-layers schemes [7]. However, enormous challenges will be created due to the excrescent difficulty and complexity in fabrication and packaging, especially in a standard CMOS foundry. Therefore, achieving decent performance and eased fabrication for edge coupling remains a great significance.

In this paper, we propose a broadband and low loss SiN edge coupler based on metamaterial design for SMF. The coupler is single layer and planar structure, significantly simplifying the fabrication process, only one step lithography and etching are needed, which can be easily fabricated in batch using the standard CMOS fabrication processes at potentially low cost. Through the edge coupler, the light coupling loss between SMF and SiN chip is only 1.60 dB at 1310 nm, and smaller than 1.86 dB in the whole O band. Moreover, the metamaterial coupler possesses wide bandwidth, the loss reaches 2.21 dB at 1550 nm, and smaller than 2.80 dB in S+C+L band. To notice, the metamaterial coupler is fully compatible with CMOS process and with a compact length of 180 μm, which can be further implemented in highly integrated photonics integrated circuits.

## 2. Design and Simulation

In order to realize efficient coupling between fiber and chip, the key is the matching of effective refractive index ($n_{eff}$) and mode field. Metamaterials enable flexible design of $n_{eff}$, mode field, phase and polarization at sub-wavelength scales. The typical structure of metamaterial in integrated photonics is the sub-wavelength grating (SWG). In contrast with conventional strip waveguide, by simply regulating the waveguide width and duty cycle of SWG-metamaterial waveguide, the $n_{eff}$ and mode field can be more effectively engineered, which profiting the light coupling. Moreover, the coupling performance often can be improved by increasing the tip number of edge coupler. Except for the tip width, the tip gap (distance between tips) can also optimize the mode field distribution at chip facet to promote the coupling performance.

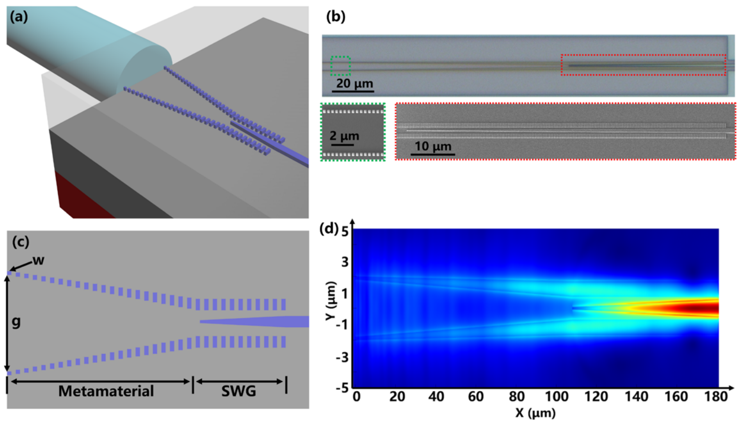


Fig. 1. The metamaterial SiN edge coupler. (a) 3D view of the coupler. (b) The optical microscope picture and detailed SEM pictures of coupler. (c) Top view of the coupler and the optimized parameters. (d) The electric field distribution of light coupling.

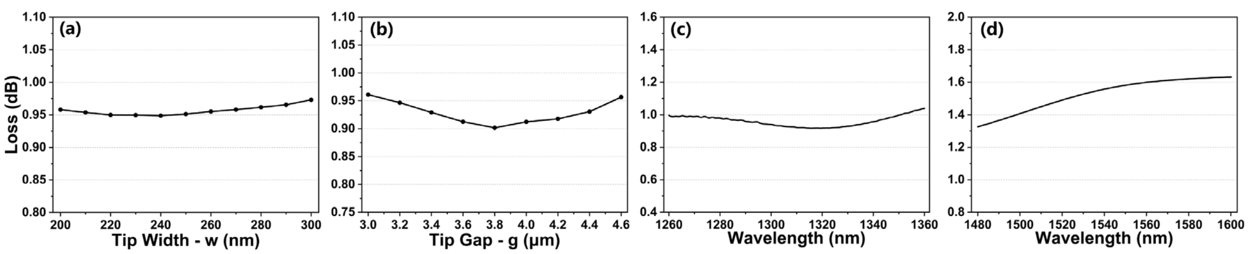


Fig. 2. The simulation results of metamaterial SiN edge coupler. The influence of (a) tip width and (b) tip gap on coupling loss. The coupling loss in (c) O band and (d) S+C+L band.

The metamaterial SiN edge coupler is shown in Fig.1, the period is 360 nm and the duty cycle is 0.5. The cycle numbers of metamaterial and SWG are set as 300 and 200, thus the total length of this metamaterial SiN coupler is 180 µm. The influences of the tip width (w) and tip gap (g) are optimized by 3D FDTD. The simulated results are shown in Fig. 2. The minimal loss is 0.95 dB at tip width of 240 nm. In the range of 200 nm to 300 nm, the coupling losses are all less than 1 dB, and the fluctuation is only 0.02 dB, indicating a tremendous fabrication tolerance. The optimal tip gap is 3.8 µm, and the coupling loss is insensitive to tip gap. The performance of the coupler in O+S+C+L band is demonstrated in Fig.2 (e) and (f), the coupling loss is 0.92 dB at 1310 nm, and 1.58 dB at 1550 nm.

## 3. Fabrication and Measurement

The metamaterial edge coupler is fabricated on a SiN-on-Insulator wafer, the thickness of top SiN device layer is 200 nm, the buried oxide layer is 3 µm thick. Benefited from the simplified structure, the coupler is defined just through single electron beam lithography process. A 5 µm thick $SiO_2$ cladding layer is deposited after the fully etching of edge coupler. A deep etching process of $SiO_2$, SiN and substrate silicon is employed to get a smooth edge facet. Finally, the integral chip is diced into several separate chips for measurement. A conventional and widely used coupler with inverse taper structure is also fabricated as a comparison.

The measurement of the edge couplers is shown in Fig.3. With the single-layer and planar metamaterial coupler with 180 µm length, the coupling loss between SMF at 1310 nm is only 1.60 dB, which is about 0.9 dB smaller than the inverse taper with 300 µm. Moreover, the metamaterial coupler is much more insensitive to wavelength than inverse taper. And the spectra ripples, mainly caused by the reflection at the chip and fiber facet, can be dramatically suppressed using refractive index matching oil. The minimal loss reaches 1.42 dB at 1302 nm, and in the whole O band, the loss is below 1.86 dB. The metamaterial coupler possesses broad working band, which can also be used in S+C+L band. The loss at 1550 nm is 2.21 dB, and smaller than 2.80 dB from 1480 nm to 1600 nm. As demonstrated in Fig.3 (d), the fabrication tolerances are researched in experiment. For the tip width from 230 nm to 250 nm, the loss variation is only 0.18 dB. And the loss variation is 0.28 dB for the tip gap ± 100 nm. Such an excellent fabrication tolerance allows the coupler to be mass-produced at low cost.

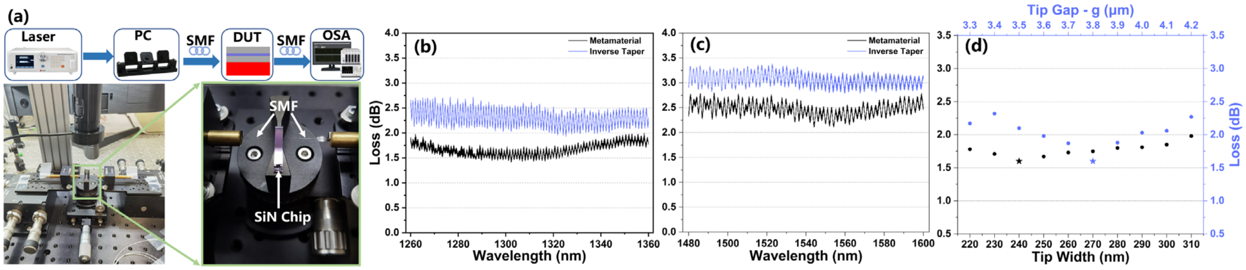


Fig. 3. The measurement of SiN metamaterial edge coupler. (a) The measurement process and platform of the edge coupling. PC: Polarization Controller, DUT: Device Under Test, OSA: Optical Spectrum Analyzer. The measured coupling losses of the metamaterial coupler and inverse taper coupler in (b) O band and (c) S+C+L band. (d) The fabrication tolerance of the tip width and tip gap.

The comparison of main performance and fabrication complexity of the metamaterial coupler in this paper and other reported couplers is presented in Table 1. Eased fabrication process is one of the prominent superiorities of the proposed metamaterial SiN coupler. Moreover, the coupler is a single-layer and planar structure, which can be fabricated on pure SiN platform without introducing complicated process and heterogeneous material system. The coupling performance is not sacrificed with tremendously evolved process. Additionally, the compact footprint of 180 μm is realized by adopting the metamaterial design, and the bandwidth is as large as 220 nm.

Table 1. The comparison of the metamaterial SiN coupler and other reported couplers. The first line represents the coupler in this paper.

| Material | Coupler Structure | Fiber Type-MFD (μm) | Loss (dB) | 3-dB Bandwidth (nm) | Length (μm) | Fabrication |
|---|---|---|---|---|---|---|
| **SiN** | **Metamaterial** | **SMF-10** | **1.60 at 1310 nm<br>2.21 at 1550 nm** | **220** | **180** | **Single layer, planar** |
| SiN[8] | Inverse Taper | SMF-10 | 0.85 at 1550nm | 130 | NA | High index cladding, Trench |
| SiN[9] | Inverse Taper | SMF-10 | 1 at 1310 nm | 230 | 500 | 3 layers SiN, RIMO a) |
| SiN[10] | Inverse Taper | SMF-10 | 3.4 at 488 nm | 0 | 275 | 2 layers SiN |
| Si[11] | Metamaterial | SMF-10 | 1.3 at 1310 nm | 60 | NA | Suspended, V-trench, RIMO |
| Si[12] | Metamaterial | Lens fiber-4 | 2.1 at 1550 nm | 100 | 85 | Single layer, planar |

a) RIMO: Refractive Index Matching Oil.

## 4. Conclusion

We report a metamaterial SiN edge coupler with broad bandwidth, low loss, simple fabrication process and high fabrication tolerance. The coupling loss between a standard SMF is only 1.60 dB at 1310 nm, and smaller than 1.86 in the whole O band. The coupler can also be used in S+C+L band, the loss is 2.21 dB at 1550 nm, and below 2.80 dB from 1480 nm to 1600 nm. Moreover, the metamaterial is a single layer and planar structure, signifying that it possesses the potential for mass production with low cost.

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