1 Introduction

With 30 years of development, especially considering the rapid breakthrough in the last decade, silicon photonics has become one of the most promising photonic integration platforms due to its low power consumption, small footprint, low cost, and availability of complementary metal-oxide-semiconductor (CMOS) fabrication technology,\(^1\)\(^-\)\(^6\) as shown in Fig. 1. The fabrication of very-low-cost photonic devices using the latest integrated circuit technology is the most important motivation for silicon photonics research and the industry. Typical silicon photonic devices include optical input/output (I/O) devices, waveguides, microring resonators (MRRs), Mach–Zehnder interferometers, multimode interferometer, and so on. Additionally, the high index contrast of a silicon waveguide offers strong light confinement, which makes it possible to integrate hundreds of photonic devices in a very small silicon chip. The high index contrast of a silicon waveguide also provides strong light–matter interactions, leading to the enhancement of nonlinearities, which makes it possible to observe evident optical nonlinearities, such as self-phase modulation, cross-phase modulation, FWM, and stimulated Raman scattering.\(^7\)

Applications of silicon photonics include optical interconnects,\(^8\)\(^-\)\(^15\) optical communications,\(^6\)\(^,\)\(^16\)\(^-\)\(^25\) nonlinear optics,\(^7\)\(^,\)\(^26\)\(^-\)\(^36\) sensors,\(^37\)\(^-\)\(^41\) nanooptomechanics,\(^42\)\(^-\)\(^45\) mid-infrared optics,\(^46\)\(^-\)\(^50\) terahertz technology,\(^51,\)\(^52\) and so on. One of the dominant applications for silicon photonics is optical signal processing, as shown in Fig. 1. Optical signal processing technologies are of great importance in optical communication systems because of their distinct abilities to overcome electronics bottlenecks, supporting ultrafast and transparent data processing. Generally, optical signal processing technologies can be divided into two classes, that is, linear and nonlinear. Linear optical signal processing includes filtering,\(^53\)\(^-\)\(^55\) differentiation,\(^56\)\(^-\)\(^58\) wavelength/mode/polarization multiplexing,\(^53,\)\(^59\)\(^-\)\(^63\) optical pulse shaping,\(^64,\)\(^65\) Hilbert transforming,\(^66\) and more.

![Figure 1](advantages_device_classification_and_applications_of_silicon_photonics.png)
Nonlinear optical signal processing exploits various nonlinear effects. A multitude of optical signal processing functionalities have been demonstrated. Commonly used nonlinear optical signal processing functionalities include wavelength conversion, data exchange, optical addressing, optical switching, optical logic gate and computing, optical format conversion, optical equalization, optical regeneration, optical coding/decoding, and so on. Traditionally, various optical materials and devices have been utilized for nonlinear optical signal processing, including semiconductor optical amplifiers, periodically poled lithium niobate waveguides, highly nonlinear fibers, and chalcogenide waveguides. However, devices based on these material platforms have relatively large footprints and also lack the ability for large-scale integration. The great success of silicon photonics offers the possibility to perform nonlinear optical signal processing on an ultracompact silicon chip. The silicon-on-insulator (SOI) platform is very suitable for nonlinear optical signal processing because of its low loss and ultracompact footprint. Moreover, nonlinearities enhanced by the tight light confinement of SOI waveguides also facilitate optical signal processing functionalities.

In this Spotlight, we focus on silicon-based nonlinear optical signal processing and review the recent research progress of nonlinear optical signal processing for handling high speed digital optical signals on silicon photonics platforms. A summary of previously demonstrated typical silicon-based nonlinear optical signal processing functionalities since 2004 is shown in Table 1. The most widely used devices are nonlinear waveguides and MRRs. Photonic-crystal waveguides are also used for nonlinear optical signal processing because of how their nonlinearities enhance slow light effects. A photonic-crystal nanocavity is also a good candidate due to its strong nonlinearities induced by ultra-small mode volume. Another important characteristic is the modulation format. The modulation formats used in early demonstrations are almost on–off keying or differential phase-shift keying formats. Beyond binary modulation formats, advanced multilevel modulation formats together with multiplexing techniques—for example, quadrature phase-shift keying (QPSK), m-ary phase-shift keying (m-PSK), m-ary quadrature amplitude modulation (m-QAM), and orthogonal frequency division multiplexing (OFDM)—have been widely used in optical fiber communication systems to increase the transmission capacity and spectral efficiency. Recently, some silicon-based nonlinear optical signal processing functionalities that employ advanced multilevel modulation formats have been demonstrated.

2 Chip-Scale Wavelength Conversion and Signal Regeneration

2.1 Wavelength conversion of OFDM m-QAM signals

For its ability to enhance the flexibility and optimize the wavelength usage of future optical networks, wavelength conversion is of great importance and is also regarded as the building block in optical signal processing. Using degenerate