NANO PHOTONICS ON-CHIP AND FORTHCOMING DIFFICULTIES THESE EXTREMELY QUICK AND ENERGY-EFFICIENT NANOSCALE OPTOELECTRONIC DEVICES

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ABSTRACT

In-chip A family of devices known as nano photonics may manipulate light on a chip to provide benefits in performance over standard building elements of combined photonics. These ultra-fast, low-power nanoscale optoelectronic devices are intended for use in a variety of applications, such as energy-efficient lighting, environmental monitoring, chemical and biological sensing technologies, and high-performance computing. Their distinctive characteristics, including their vast evanescent field, compactness, and most crucially, their flexibility to be modified according on the needed application, are making them an increasingly appealing building element in a range of systems. This article outlines the latest developments in integrated nanophotonic devices and the applications that have been shown for them, ranging from encryption to all-optical processing on a chip, logic gates on a chip, and mid-infrared and overtone spectroscopy. within a chip. The examined devices allow for the use of optical waveguides in a range of optical systems, opening up a new area in on-chip nano photonics. are intended to quicken the transfer of nano photonics from research to commercial use.

KEYWORDS: deep-learning; overtone spectroscopy; parity time; plasm onics; waveguide.

INTRODUCTION

Following the 20th century, which was seen as the age of electronics, the 21st century is the era of photonics and quantum optics. The reduction in size of optoelectronic elements is motivated by the need for quick and easy information processing, sensing, and other functions in a wide range of applications, including non-destructive detection, banking, healthcare, communications, cyber security, and defense. It's anticipated that quantum and all-optical computers on a chip will be widely used due to the extent of shrinkage, low cost, and resilience of microfabrication techniques that have made mobile phones and laptops so commonplace. Planar dielectric waveguides are used in the field of photonics known as "on-chip photonics" or "integrated photonics." manufactured on a chip, such the ones that Ref. [1] summarizes. The new and quickly expanding subfield of on-chip photonics known as on-chip nano photonics uses waveguides are either hybrid waveguides (composite waveguides), which are conventional waveguides with nanoscale overlayers of slab film [3], nano antennas [4, 5], or metamaterial overlayers [6–9], or they are of nanoscale dimensions as outlined in Ref. [2]. Furthermore, by using the concepts of guided-wave optics, on-chip nano photonics enables the design, production, and integration of several nanophotonic components on a single substrate. The configuration of on-chip nanophotonic technologies requires the fusion of many light-related fields, including silicon, plasmonics, nano photonics, and guided-wave optics.

both waveguide technology and photonics. Historically, the fundamental component of photonic integrated circuits (PIC), optical waveguides, were mostly constructed from transparent lenses, metals that reflect light, and several kinds of optical thin sheets [10]. According to Snell's law, Fermat's principle, Fresnel's equations, and Fresnel–Kirchhoff's diffraction formula, certain bulk materials preferentially refract and reflect light [11]. The diffraction limit and other limitations imposed by classical theories, as well as the reduction of photonic integrated circuit complexity and cost, are among the primary obstacles facing the ever-increasing interest in improving the performance of classical optical waveguides and resolving the fundamental issues. Over the last few decades, optical waveguides have been manufactured on a larger scale, enabling the use of dispersed light with dimensions smaller than wavelengths. by subwavelength structures, where it is practically possible to modify the propagation of light [12, 13]. Additionally, the rigorous designs of complicated structures with multiscale characteristic dimensions have been made easier by full-vectorial electromagnetic computational techniques [14]. Figure 1 displays a bar chart of on-chip nano photonics publication records (retrieved from Web of Science using the keywords on-chip nano photonics, waveguides) that demonstrates the field's rapid progress and expansion from 2000 to 2019. Subwavelength light-matter interaction at the nanoscale is combined with both classical and quantum effects in a variety of functional materials for on-chip photonics, including phase-change materials [15, 16], semiconductors [17], and noble metals 2D materials [20, 21], as well as materials [18, 19]. These so-called metamaterials [22] provide hitherto unheard-of chances to enhance the functionality of traditional optical equipment. Artificial materials with subwavelength characteristics are called meta materials .They function as tiny anisotropic light scatterers when utilized as a waveguide overlayer. Thus, it is possible to manipulate light's phase, amplitude, and polarization to produce the required optical response on a semiconductor. By adding metamaterials to on-chip photonic devices, waveguide performance may be tuned. For example, waveguide facet reflection losses can be decreased by using antireflective structures [23, 24]. useful index for changing the propagation modes [25], and a "hiding carpet" for concealing an item on a chip [6]. Here, we examine the phenomena connected to the spread of and light manipulation in waveguides made of dielectric, plasmonic overlayer waveguides, or waveguides covered with metamaterials. In this work, we provide an updated overview of the state-of-the-art in on-chip nano photonics, pointing out areas where on-chip nanophotonic designs might be particularly helpful and highlighting optical devices for new applications that require more improvement. The format of the paper is as follows: The building blocks needed for the on-chip design are the subject of Section 2. The designs and spatial field distributions of nanophotonic devices. Section 2.1 discusses passive components, while Section 2.2 discusses active components of the examined building blocks. elements. Some developing applications of on-chip nano photonics, such the overtone spectroscopy on a chip described in Section 3.1, are suggested in Section 3. Furthermore, we offer the basic ideas and techniques that were investigated and applied to investigate subwavelength structuring in optical waveguides and multi-layer systems on a chip. We go over the fundamentals of field enhancement and concentration in plasmonic structures. We provide further details on the theory of wave propagation in various periodic mediums and a few of its uses in waveguides and multilayer structures. Lastly, we go over the fundamentals of materials with subwavelength structures and their applications. to regulate the chip's electromagnetic fields. Major developments in on-chip quantum nano photonics are the subject of Section 4. The modulation of light-on-a-chip using nanoparticles or meta surface overlayers

is the main topic of Section 5. We describe how hybrid modes in dielectric and plasmonic overlayers on waveguides are excited and show how the evanescent field of such a device may be controlled to produce a waveguide with new functionality. We show the design and implementation of meta surfaces that can minimize waveguide coupling losses and that can change the eigenmodes that a silicon waveguide supports. A review is given of research projects that use materials with subwavelength dimensions to create innovative chip scale devices. Furthermore, the useful There are suggestions for a new type of surface plasmon resonance (SPR) sensor on a chip. Section 6 provides an overview of the state of development for on-chip nanophotonic platforms, highlighting both the unique opportunities and the remaining challenges that can be explored with chip-scale platforms, such as on-chip energy-conserving logical elements in Section 6.2 and on-chip trapping schemes in Section 6.1.

ON-CHIP PHOTONICS

The optical passive waveguide is the fundamental building block of on-chip photonics; it is a transparent dielectric structure.

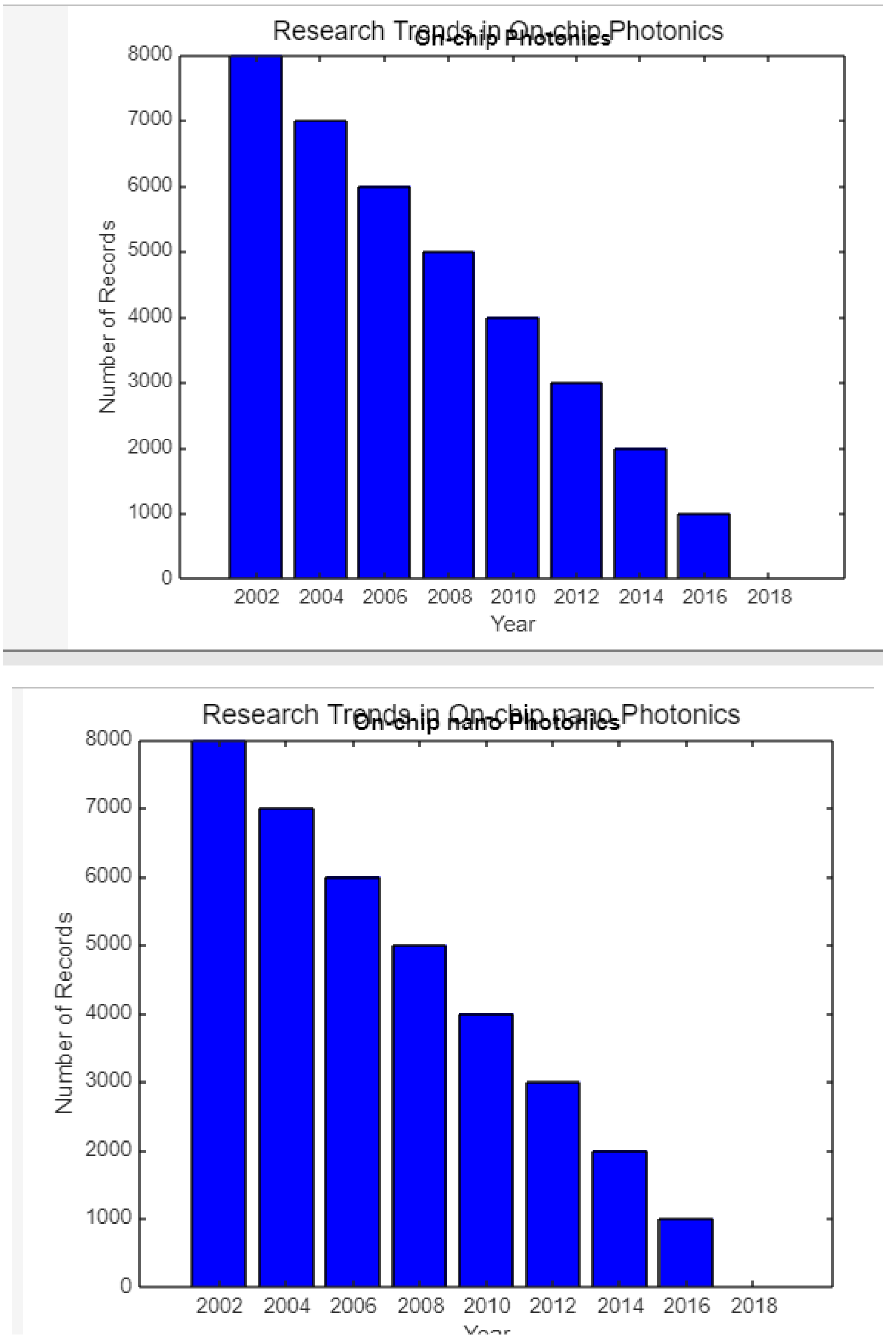

Figure 1: Evolution of on-chip nanophotonic devices over the years 2000–2019:

Composed of a narrow cross-section, it is able to contain and convey energy, as seen in Figure 2a. The optical fiber is a cylindrical waveguide; the In on-chip photonics, planar waveguides consist of a minimum of three layers: the substrate, the guiding layer (also known as the core), and a cladding (which might be air or another material). Total internal reflection (TIR) has the effect of guiding the light within the waveguide core [11]. We recommend that readers use textbooks that expound on the theory of guided-wave optics, such as Snyder and Love [26], Hunsperger [27], and Chrostowski and Hochberg [28], in order to gain knowledge of the propagation of waves in each waveguide configuration.

PASSIVE COMPONENTS

As illustrated schematically in Figure 2a, common passive waveguide designs include slab, strip loaded, ridge, rib, buried, and diffused [1]. Every arrangement has distinct qualities and are suitable for a variety of uses. Ridge waveguides' strong overlap with the superstrate makes them a great option for sensing. Similar to optical fibers, buried waveguides are a viable option for optical signal transmission since they are coated with cladding. When specific waveguide and material boundary conditions are met, light in a waveguide propagates as a discrete electromagnetic wave, which is a solution of the wave equation. Waveguide modes are discrete field distributions [26]. The waveguide's size and refractive index determine how much of a one or more guided modes. Numerical findings of basic modes computed for typical passive waveguide structures are displayed in Figure 2b. A rib waveguide would be bigger dimensions to facilitate single-mode operation than the ridge waveguide, which has a simpler coupling process. Furthermore, there is less interaction between the mode and that lowers sidewall scattering is the waveguide.A significant portion of the mode in ridge waveguides lies beyond the bounds of the guiding layer, which makes the ridge waveguide is recommended for applications dependent on evanescent fields [1, 37]. Unlike other waveguide systems, the slot waveguides (Figure 2b) can be singlemode and extremely restricted in tiny dimensions. This design is good for sensing because the mode propagates in the low-index medium [38]. It is essential to remember that, while a mode moves through a waveguide, a component of it lives outside of the physical boundaries of the waveguide and is referred to as the evanescent wave (or field). A nonpropagating wave is an evanescent wave. Waveguide evanescent fields can be assessed using the field's penetration depth (dp). The distance at which the field's strength or intensity decreases to the waveguide surface is known as the penetration depth. 1/e, or roughly 37% of its surface value, is what is meant by

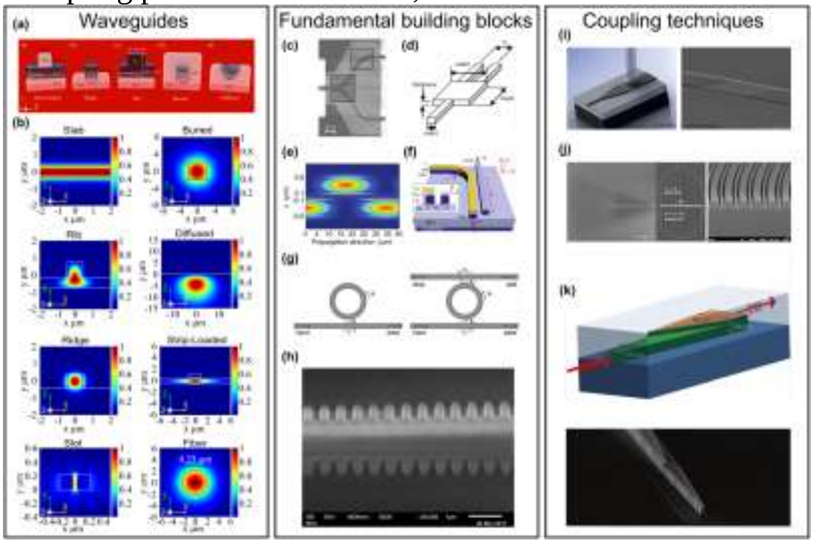

Figure 2: Key passive components in on-chip nano photonics

$$d_P = \frac{\lambda}{\sqrt[2\pi]{n_2^2\, sin(\theta i) - n_1^2}}$$

where θi is the incidence angle to the normal of the interface between the waveguide core and the cladding, and n2 and n1 are the corresponding refractive indices of the waveguide core and cladding. siding. The exponential solution of the wave equation solved in Cartesian coordinates for planar waveguides (or second kind of modified Bessel functions for fibers, then the wave equation is solved in cylindrical coordinates) is the mathematical description of the evanescent field, a side effect of TIR [26]. When it comes to the fundamental mode (zero order mode m = 0), the guided wave approaches the critical angle (normalized effective index b ≥ 1) and the V-number is very small (h/λ ≥ 1).

ACTIVE COMPONENTS

As indicated above, coupling light to the waveguide is one of the main problems in on-chip nanophotonics. One solution to this issue is to directly construct the source. within a chip. By creating the laser on a chip and using a low pump pulse energy, the coupling efficiency may be increased. A Si wire ring resonator was utilized to create a tunable narrowband laser on a chip [43, 44]. We observe that silicon cannot be employed for broadband sources because of its short band-gap, which reduces infrared emission [57]. However, silicon nitride may be employed for supercontinuum production, which allows for broadband generation from visible to mid-infrared [57]. pulsed lasers on a chip for effective and localized light control [62, 63], or octave-spanning supercontinuum creation [61], as seen in Figure 3a, b. Optical modulation is a crucial component of on-chip photonics. Modulation is the process of altering the frequency, amplitude, or phase of light by adjusting the medium's refractive index. Applying a field to a material and causing an electro-optic effect is the primary way to alter its refractive index [64]. There are two categories for this effect: electro-refraction, which modifies the complex refractive index's real component, and electro-absorption, which modifies the complex refractive index's imaginary part. Nevertheless, silicon, a key component of on-chip photonic devices, has a weak electro-optical phenomenon.

Consequently, the dispersion of plasma produces a modulation effect that is more effective. Although not very strong for electro-absorption modulation, this effect can be utilized for phase modulation, which may then be adjusted to adjust the intensity through the use of ring resonators or Mach-Zehnder interferometers. The change in order of magnitude is improved by this. There aren't many waveguide-based modulation setups available. By introducing phase shift into one of its arms (Figure 3c), a Mach-Zehnder may be utilized as an amplitude modulator [58, 65]. Similarly, a ring-resonator with a small footprint and low driving voltages [46, 66] can be employed as an amplitude modulator.

Detectors can also be monolithically integrated on the same planar substrate in order to detect an optical signal on a chip. The Schottky diode construction is extensively used for this. utilized. A Schottky barrier is created by the placement of a metal layer on a doped semiconductor in this type of diode. The carrier produced by the absorption becomes detectable after it has sufficient power to go beyond this obstacle. A Schottky diode-based detector may be made on a chip by applying a metal layer on doped silicon in order to implement the detecting principle [59]. A low Schottky barrier may be created by using a gold strip as a metal layer, which raises the device's quantum efficiency [67]. Germanium is another material that is frequently utilized in on-chip detectors.

In comparison to silicon, germanium is able to obtain a greater near-infrared absorption coefficient. For photodetectors at the telecommunication windows, germanium waveguide photodetectors that are evanescently linked can be employed on an SOI platform [60]. Recently, graphene has become a key component in the tuning of active devices in on-chip photonics to realize new capabilities [69]. The two-dimensional layer of graphene is hexagon-shaped carbon with strong broadband absorption [72] and carrier mobility [70, 71]. Fast gadgets can be designed thanks to these characteristics [73]. Light modulation is one of the most common uses for graphene. One may modify the graphene's characteristics to adjust the amplitude by putting a layer of graphene over a silicon-on-insulator (SOI) waveguide (Figure 4a, b) and applying bias [68, 74]. Furthermore, one may alter the resonance's spectrum position by putting graphene atop a silicon nitride ring resonator (Figure 4c, d) [45, 47].

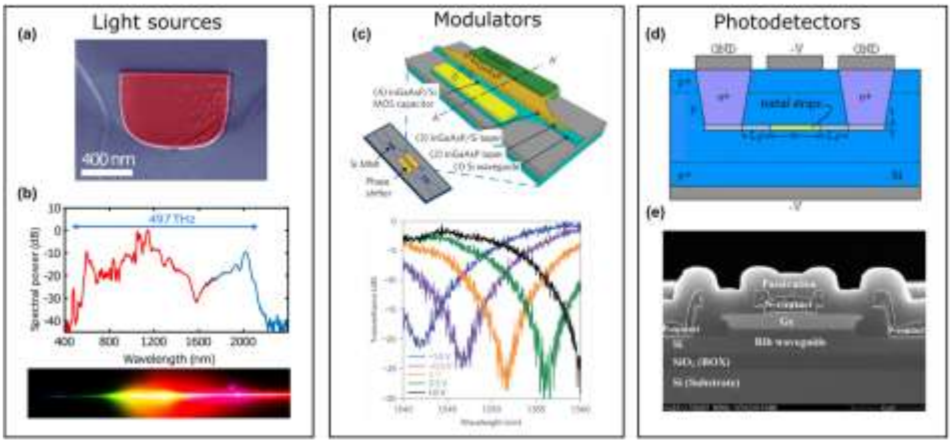

Figure 3: Key active components in on-chip nano photonics.

GUIDED-WAVE DEVICES FOR EMERGING APPLICATIONS

Recently, new uses for guided wave devices on a chip have been discovered, including overtone spectroscopy. The

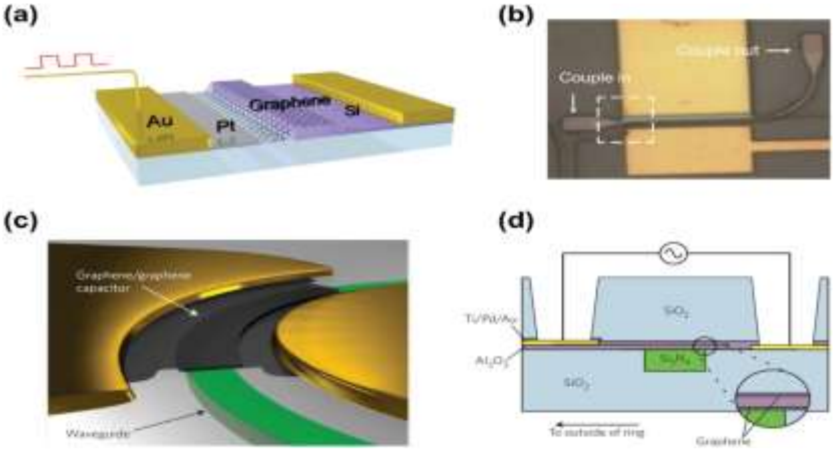

Figure 4: Graphene based devices.

Manipulation of light on a chip with meta surfaces

Man-made surfaces, or meta surfaces, have the ability to manipulate electromagnetic fields and perform functions that are not possible with natural materials. Metas urfaces make it possible to govern the subwavelength dimensions of the phase, amplitude, and polarization. They are composed of subwavelength features called scatterers, or nanorods and nanoholes. For example, the effect of negative refraction can be produced by generating negative relative permittivity and permeability values. When combining positive indexed materials and double negative media, metamaterials can be employed as a phase correction medium. A refractive index of -1 or below permits the creation of a super lens, which overcomes the guided wave optics' square wavelength focusing constraint [160]. Furthermore, meta surfaces enable the creation of refractive indices that are almost zero in which one or more parameters—such as relative permeability or permittivity are improving the nonlinear refractive index [161] and are almost zero [22]. One of the more intriguing uses of metamaterials is a cloaking effect of invisibility. Waveguides may be used to illustrate the invisibility cloaking effect, as established by Galutin et al. [6]. This occurs when the meta surface overlayer alters an item's scattering fields such they do not interact with the evanescent field, making the object invisible. Figure 8a depicts the composite plasmonic waveguide construction. The modal distribution and surface intensity in a channel photonic waveguide with a cloaking meta surface overlayer were investigated. On the composite plasmonic waveguide with the nano-spacer, the plasmonic meta surface is positioned. High-performance nano-spacer

composed of Si has aided in the coupling to the hybrid plasmonic modes and light confinement in the area around the meta surface boundary. The illumination Because of the tailored effective permittivity, which also prevents the scattering effect, manipulation is possible. The refractive index and transformed grids of the evanescent field waveguide cloak are displayed in Figure 8b. The surface intensities of a waveguide evanescent field cloak on a chip with (up) are displayed in Figure 8c. Refer to the cylindrical object, the waveguide, and the (down) cloak. A waveguide's meta surfaces can be used to display mode conversion effects. Dielectric meta surfaces carved in silicon waveguides can be used to achieve mode conversion, according to research by Greenberg and Karab chevsky [25]. In order to effectively connect the To get around the propagation constant mismatch between the mth and nth modes in a waveguide, the meta surface must supply an effective wavevector keff. The authors' suggestion Figure 8d depicts an SOI waveguide strip waveguide with a periodic index perturbation along the propagation path. The computed results for the TE0–TE1 (Ey component) mode conversion device are displayed in Figure 8e. These results include the input and output mode profiles, the refractive index profile needed for conversion, and the mode evolution along the direction of propagation. We found conversion efficiencies of 96.4% between the TE0–TE2 across 6.32 μm and 95.4% between the TE0–TE1 modes over 8.91 μm contact distance.
For constructive energy transfer from one mode to another, the resultant coupling coefficient must vary in a sinusoidal fashion as a function of interaction distance.to another.

ON-CHIP OPTICAL VORTEX

As the need for tiny integration grows, integrated photonic devices on various material platforms are being developed for new applications, one of which is a on chip Recently, biosensors, on-chip quantum technologies, and on-chip optical vortex-based detectors in plasmonic materials have also been developed [162].

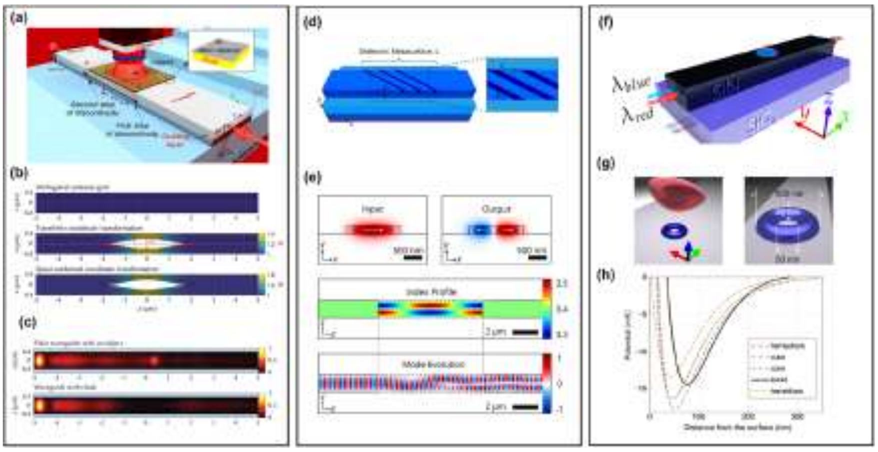

Figure 5: On-chip nanophotonic devices for emerging applications:

A light beam that propagates such that the wavefront has a topological structure and the phase experiences phenomenological singularity is known as an optical vortex. because of the helicoidal spatial wavefront surrounding this phase singularity, with topological charge. Several fields, including optics and acoustics, use this type of topological structure. Investigating the incoming beam's phase, polarization, and amplitude is necessary to comprehend the singularity's impact. It is possible to learn that the phase cannot be determined when investigating these unique beam qualities, and that the amplitude and polarization both disappear. These discoveries were first presented in 1974 as a novel idea in wave theory. Nye and Berry's theoretical work included reports on the detection of "dislocations" [163]. Science [164] published the first research on an optical vortex emitter combined with silicon on a chip. Possessing a detector and emitter On-chip optical vortex-based photonic devices would require a significant advancement to be monolithically integrated on the same chip. Through their experimental effort, Feng and colleagues created a unique on-chip optical detector that enables

thorough characterization of the phase singularities and polarization based on plasmonic Spin-Hall nano-grating. In contrast to previous cutting-edge systems, their detection approach enables the simultaneous identification of singularities. It's interesting to note that complex alignment is not necessary for the detector created by Feng and colleagues.
Its foundation is an asymmetric metallic array with distinct gratings on the top and bottom of the array. steady. The direction at which an excited surface plasmon polariton (SPP) propagates depends on the particular surface topology. The asymmetry makes it possible to distinguish the sign of the topological charge (phase), whereas the incoming beam's spin affects the Spin-Hall slits. The arrangement of nano slits orientated at π/2 results in what are known as Spin-Hall slits.

The chiral response of the detector is caused by this orientation of the nano slits. The inverted chiral response occurs if the slits are flipped. The authors are able to differentiate between the right-circularly polarized (RCP) and left-circularly polarized (LCP) beams because to this unique architecture. Put simply, an SPP that travels at an angle θ to one of the four would be excited by a beam impinge on the detector.

quadrants, refer to Reference [162]'s Figure 1. The sign of the topological charge and the beam's polarization (RCP/LCP) are determined by the quadrant in which the SPP propagates. The perspective The magnitude of the topological charge is determined by θ. Large-scale integrated photonic applications are made possible by these devices' ultra-compact size and incredibly straightforward operation [164, 165]. These features also make it simple to connect these devices with other on-chip components like modulators and lasers to create photonic integrated circuits.
Demonstrating the functioning of on-chip optical vortex-based devices would be the next significant achievement. by removing the plasmonic materials' inherent Ohmic losses and investigating alternative surface waves, such Bloch waves, which may travel over lossless dielectric materials (166–169; 1, 23, 37,). In the upcoming years, one may anticipate notable advancements in integrated photonics toward optical vortex-based on-chip innovative devices.
Global trends and future challenges

One of the main benefits of on-chip nano photonics is its capacity to streamline the process of investigating light-matter interaction on a chip at the size where optical, The qualities of electronics, structures, heat, and materials are intricately linked. The long-term objective of on chip nano photonics is to control light quickly—within a few oscillation cycles of the light wave—in a tiny device made up of only a few atom layers using signals carried by a small number of photons. This technology has emerging uses, such as ultra-high sensitivity biosensors for dangerous viruses and quantum technology. Through converting electronics-based technologies to photonics, specific Certain subfields of nano photonics, such programmable multifunctional nano photonics [171] and topological photonic systems [170], may be implemented on-chip. It has also been investigated to integrate acousto-optic interactions arising from stimulated Brillouin scattering [172]. A number of less expensive and more traditional platforms for the creation and/or augmentation of photonic integrated circuits have also been suggested, such as graphene [176], van der Waals materials [174], photonic crystals [175], and InP [173]. Global trends and upcoming problems in the field of on-chip nano photonics are shaped by notable developments. We enumerate a few of them in the subsection that follows.

EVANESCENT TRAP WITH PHOTONIC WAVEGUIDES

Tailored light potentials for atom trapping by evanescent fields from nanofabricated photonic waveguides have the potential to become a crucial component of ultra-cold atom-based quantum technology devices. It has previously been possible to construct optical lattices and atom trapping by evanescent fields above the glass surface [177], in optical fibers [178], and in nano waveguides [179].

Nevertheless, it has never been possible to create a dense (few tens of nano meters between each site) optical lattice with atoms evanescently trapped at a nanoscale distance of around 50 nm from the waveguide surface.

Practically speaking, this will enable strong atom-to-atom and photon-to-atom interactions. The waveguides and other components can be combined on the same chip. optical components, including single photon operations [182], atom manipulation [181], and light cavities for atom detection [180, 181]. In addition to the practical benefits already discussed, integrated waveguides provide intrinsic qualities that other atom trapping systems are unable to achieve. For instance, the spacing between consecutive traps can be on subwavelength scales, and curved structures can be created, in contrast to atomtrapping in optical lattices [128, 183]. The atoms are trapped by evanescent homogenous light fields as opposed to the standard atom chip technology, which is based on magnetic trapping and guided by current-carrying wires. By doing this, negative consequences like fragmentation [184, 185] and longevity reduction from technical noise from the present source are avoided. The atoms are transportable.

more closely to the chip surface without experiencing Johnson noise from the metallic surface [186]. Si3N4 nano waveguide platform constructed from silicon nitride Mirrors have been suggested as a core for the collective cold atom–light interaction through evanescent field coupling [179]. This system suggests securing atoms at a minimum of 150 nm above the waveguide using bi-chromatic evanescent field atom traps. A comparable setup, seen in Figure 8f, has been suggested [37] to employ an all-dielectric device to trap atoms utilizing a silicon nitride ridge waveguide with a nano-antenna on top (Figure 8g). It was demonstrated that the atoms may be trapped in the toroidal nano-antenna at a distance of around 70 nm from the surface. (Figure 8h).

ENERGY-CONSERVING OPTICAL ELEMENTS

Reducing energy consumption is one of the biggest problems in information processing and computing, not just because it will help with the enormous number of electric power utilized by the computer industry, including companies like Facebook, Google, and Amazon, as well as to let computers to run at a faster frequency without melting from the increased heat. For example, 1.5% of the world's power is used to cool data centers throughout the globe. Theoretically, reversible gates may conserve energy in addition to the data, and reversible devices may be constructed fully of energy-conserving components [187]. This formalism applies both linear and nonlinear unitary transformations to optical components that are conserved, such optical waveguide based directional couplers.

CONCLUSION

This overview demonstrated the quickly expanding area of on-chip nano photonics, covering the most recent innovative devices and technologies, the difficulties, and the plans for the direction of the field's research. A thorough analysis has been conducted on the development of passive optical waveguides as real devices, including switches, detectors, filters, modulators, and light sources on a chip. On-chip nano photonics has the ambitious objective of enabling sophisticated functions like energy conversion, biological sensing, computation, and cryptography to be carried out on a single device.

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