Abstract  Surface plasmon propagating modes supported by metal/dielectric interfaces in various configurations can be used for radiation guiding similarly to conventional dielectric waveguides. Plasmonic waveguides offer two attractive features: sub-diffraction mode confinement and the presence of conducting elements at the mode-field maximum. The first feature can be exploited to realize ultrahigh density of nanophotonics components, whereas the second feature enables the development of dynamic components controlling the plasmon propagation with ultralow signals, minimizing heat dissipation in switching elements. While the first feature is yet to be brought close to the domain of practical applications because of high propagation losses, the second one is already being investigated for bringing down power requirements in optical communication systems. In this review, the latest application-oriented research on radiation modulation and routing using thermo-optic dielectric-loaded plasmonic waveguide components integrated with silicon-based photonic waveguides is overviewed. Their employment under conditions of real telecommunications is addressed, highlighting challenges and perspectives.

Dielectric-loaded plasmonic waveguide components: Going practical

Ashwani Kumar¹, Jacek Goscinia³, Valentyn S. Volkov¹, Sotiros Papaioannou²,³, Dimitrios Kalavrouziotis⁴, Konstantinos Vyrsokinos³, Jean-Claude Weeber⁵, Karim Hassan⁵, Laurent Markey⁶, Alain Dereux⁵, Tolga Tekin⁶, Michael Waldow⁷, Dimitrios Apostolopoulos⁴, Hercules Avramopoulos⁴, Nikos Pleros²,³, and Sergey I. Bozhevolnyi¹,*

1. Introduction

Plasmonics, in recent past, has been a frontrunner in the ongoing efforts within the nanophotonic community for developing next-generation chip-scale technologies [1–3]. The accelerated interest in plasmonics impelled by the developments of several important waveguide configurations involving surface plasmon (SP) modes has put forward plasmonics as the “beyond photonics” alternative for chip-scale platforms. Surface plasmon polaritons (SPPs) represent electromagnetic excitations, which are coupled to the surface collective oscillations of free electrons in a metal, thus forming two-dimensional bound waves propagating along metal/dielectric interfaces and exponentially decaying into neighboring media [4, 5]. The existence of SP propagating modes, which are spatially localized near metal/dielectric interfaces [6], has been known for decades, but the renewal and explosive growth of interest to SP waveguides occurred relatively recently when it was realized that SP modes in metal nanostructures may lead to the localization of guided-light signals far beyond the diffraction limit for electromagnetic waves in dielectric media [7].

Enormous efforts have been devoted in the past decade to realize different SPP-based waveguide configuration, each offering specific advantages and suffering from particular limitations. These intensive efforts have been primarily driven by the perspective of combining the benefits of both electronic and photonic technologies in terms of their compactness and high bandwidth, respectively [6]. Among all different configuration developed so far, the presence of metal in plasmonic waveguides rather presents a contrasting situation in terms of a trade-off between mode confinement and propagation loss of the plasmonic waveguides. The metal layer, which forms a very integral part

---

¹ Institute of Technology and Innovation, University of Southern Denmark, DK-5230 Odense M, Denmark
² Department of Informatics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
³ Informatics and Telematics Institute, Center for Research and Technology Hellas, 57001 Thessaloniki, Greece
⁴ School of Electrical and Computer Engineering, National Technical University of Athens, 15780 Zografou, Athens, Greece
⁵ Institut Carnot de Bourgogne, University of Burgundy, F-21078 Dijon Cedex, France
⁶ Fraunhofer Institute for Reliability and Microintegration, 13355 Berlin, Germany
⁷ AMO GmbH, 52074 Aachen, Germany

* Corresponding author: e-mail: seib@iti.sdu.dk

© 2013 The Authors. Laser Photonics Rev. published by Wiley-VCH Verlag GmbH & Co. KGaA Weinheim.
of plasmonic waveguides, is also responsible for the inevitable ohmic losses. Since it is metal boundaries that enforce squeezing of EM fields of SPP modes in the lateral cross section, a decrease in SPP mode cross section is accompanied by an increase of the fraction of EM energy being concentrated inside the metal, which eventually leads to increased propagation losses [8]. To date, various plasmonic waveguides have been proposed and investigated, which has led to the establishment of the subdiscipline of integrated plasmonics. The development of long-range SP waveguides featuring relatively low propagation losses [8–10] and experimental demonstration of SP nanoguides in the form of metal nanowires [11–13] was followed by the realization of channel plasmon polariton (CPP) waveguides [14] representing V-grooves cut into metal surfaces [15,16] and dielectric-loaded SPP waveguides [17–19]. Different SPP waveguide configurations developed exhibit different characteristics (mode localization, propagation and coupling losses) favoring different applications ranging from on-chip sensing to active and dynamic nanophotonic components, quantum plasmonics and optical interconnects [1–3, 20, 21].

Considering the ever-increasing demands of large bandwidth, small footprint and energy efficiency of integrated components and circuits [22], plasmonic waveguides offer two very attractive features: subdiffraction lateral confinement of propagating modes and the presence of metal electrodes right at the mode-field maximum, enabling highly efficient control of waveguide-mode characteristics [23, 24]. The metal present in plasmonic waveguides introduces unavoidable losses (ohmic heating), and this was, for a long time, considered to be the major roadblock for plasmonics to be used for practical applications. But the fact that the same thin metal circuitry can be exploited to carry optical signals as well as electrical control has emerged as the biggest advantage of SPP waveguide-based components when compared to their photonic counterparts [25].

This ability to transmit light and electricity in the same component simultaneously opens up interesting possibilities for hybrid electro-optical integration [26]. In this regard, among various plasmonic waveguide structures proposed so far, dielectric-loaded SPP waveguide (DLSPPWs) have been considered highly promising for enriching the functional portfolio of plasmonics through the utilization of their dielectric loading properties [27, 28].

This review aims to serve as an introduction to DLSPPW technology and some of their most promising functionalities. We summarize some of the recent developments related to DLSPPW-based plasmonic waveguide components employed under the conditions of real interconnect systems and put forward the perspective of plasmonics as one of the most promising candidates for chip-scale technology. A brief introduction to DLSPPW technology in terms of mode confinement and propagation length and its heterointegration with the silicon-on-insulator (SOI) platform is presented. Power monitoring in DLSPPWs is then discussed as an interesting possibility for hybrid electro-optical integration of plasmonic waveguides. Next, we discuss the ability of DLSPPWs to sustain signal integrity under realistic high repetition rate traffic conditions and high-quality functional switching performance: two very important requirements for employing DLSPPW technology in real interconnect systems. Later, we discuss the possibility of improving the performance of DLSPPW components by changing the polymer loading to a more efficient material and also some improvement in geometrical configuration that will lead to a new class of waveguides called long-range DLSPPWs.

2. DLSPPWs: mode profile and heterointegration

The DLSPPWs, in the present context, are formed by placing a polymethylmethacrylate (PMMA) ridge with a cross section of 500 nm in width by 600 nm in height as the dielectric material on top of a 65-nm thick and 3-μm wide gold strip (Fig. 1a). This geometry provides us with full 2D confinement in the plane perpendicular to the propagation direction. The calculation of plasmonic mode properties for this geometry has been performed by a finite-element method implemented in the commercially available software COMSOL multiphysics. This geometry is one of the most popular for plasmonic waveguides due to the fact that PMMA can work as both resist and the dielectric core for the DLSPPW. It is hence quite a convenient and simple process to fabricate plasmonic devices based on DLSPPW using deep-ultraviolet (UV) lithography for those devices with larger dimensions working at telecom wavelengths [29] or standard E-beam lithography (EBL) for those working in the near-infrared [30]. The SP mode-field distribution calculated for this geometry at the operating wavelength

![Figure 1](image-url)
of 1550 nm exhibits tight lateral confinement, which is clearly subwavelength (Fig. 1b). The waveguide geometry has been carefully selected to ensure the single-mode operation at telecom wavelengths for TM-polarized light. The typical propagation length for these waveguides at 1550 nm is 50 μm. Figure 1c illustrates the variation of the effective index and propagation length of DLSSPPWs as a function of PMMA ridge width for two different configurations calculated for the wavelength of 1550 nm.

In comparison with other waveguide configurations, DLSSPPWs represent an attractive alternative by virtue of being naturally compatible with different dielectrics and ensuring a rather good trade-off between mode confinement and propagation distance. The first feature is very important for realization of dynamic components by making use of material (e.g., thermo- and electro-optic) effects, while strong mode confinement and long propagation distances are required for realization of compact and complex plasmonic circuits. For example, CPP waveguides realized by V-grooves cut into metal layer offer very high subwavelength confinement compared to DLSSPPWs but suffer from high propagation losses when used with dielectric claddings, which are actually not that easy to introduce. On the other hand, long-range SP waveguides, that are also naturally compatible with dielectrics, feature in comparison very long propagation distances (owing to the symmetric dielectric environment) but very poor mode confinement.

For DLSSPPWs, in addition to the comparatively tight mode confinement at the bottom of a PMMA strip (Fig. 1b), mode electric-field components penetrate into the substrate due to the finite thickness of metal stripes (assuming that the stripes are wide enough, typically > 3 μm, to avoid the direct field penetration). From the calculations presented above, it is clear that the real part of the effective index of the DLSSPPW is smaller than the refractive index of the substrate, so the DLSSPP mode is actually a leaky mode and the degree of leakage is determined by the metal thickness. This kind of leakage, although leading to some additional losses, does also provide an effective means of imaging SPP waves. The interfacing of Si to DLSSPPW was realized by means of a butt-coupling whose specifications are derived from a parametric analysis in terms of the width of Si waveguide, the vertical offset between the two types of waveguides and a longitudinal gap in the metallic strip [36]. As can be seen in Fig. 2a, a funnel structure is used at the interface of the Si and DLSSPP waveguide, this compensates for losses occurring due to any possible misalignment during the fabrication process. With the high coupling efficiency, the propagation loss in DLSSPP can be directly measured without the need for more complicated setups like LRM or scanning microscopy.

This allows both plasmonic and Si-photonic functionalities to be incorporated on the same substrate, paving the way to the eventual monolithic integration of photonics, plasmonics as well as electronics all on the same chip. In a significant development, heterointegration of DLSSPPWs with SOI waveguide was first demonstrated by Briggs et al. [34] with a coupling efficiency of almost 80% at telecom wavelengths.

In yet another recent demonstration of heterointegration [35], the SOI motherboard that houses the heterointegrated plasmonic and Si waveguide technologies relies on a silicon rib waveguide platform providing enhanced flexibility and compatibility for interfacing low-loss Si photonic waveguides with DLSSPPW structures. Taking into account that plasmonic structures only support the TM optical mode, the silicon rib waveguides were designed to have a cross section of 400 nm in width and 340 nm in height with a 50-nm thick slab that are able to feature low-loss TM light propagation. The hosting area for plasmonic structures was created by etching a 200-nm deep cavity in a silicon dioxide substrate. Within the cavity, DLSSPPW structures were fabricated comprising 65-nm thick and 3-μm wide gold strips supporting PMMA ridges with cross sections of 500 × 600 nm². Figure 2a shows the schematic as well as microscopic picture of a 60-μm long straight DLSSPPW interfaced with the Si waveguide. The interfacing of Si to DLSSPPW was realized by means of a butt-coupling whose specifications are derived from a parametric analysis in terms of the width of Si waveguide, the vertical offset between the two types of waveguides and a longitudinal gap in the metallic strip [36]. As can be seen in Fig. 2a, a funnel structure is used at the interface of the Si and DLSSPP waveguide, this compensates for losses occurring due to any possible misalignment during the fabrication process. With the high coupling efficiency, the propagation loss in DLSSPPW can be directly measured without the need for more complicated setups like LRM or scanning microscopy.

**Figure 2** (a) Schematic and microscopic image of straight DLSSPPW heterointegrated with Si waveguide employed for transmission measurement. (b) Picture of grating coupler employed on the chip. (c) Efficiency plot of the grating coupler.
near-field optical microscope (SNOM). A cut-back measurement for a variety of fabricated hybrid Si-DLSPWP waveguides exhibited a coupling loss of 2.5 dB on average. Moreover, the propagation losses for Si and DLSPPW waveguides were found to be approximately 4.5 dB/cm and 0.1 dB/μm respectively, in good agreement with that reported in [34].

Another important issue that needs to be discussed here is the scheme of coupling light in and out of a chip containing DLSPPWs heterointegrated with photonic waveguides. Conventional schemes to excite plasmonic modes such as the Kretschmann configuration [37] is not favorable as far as miniaturization at the chip level is concerned. In this regard, employing a single-mode optical fiber to couple light in and out of long-range SPP waveguides [38] as well as DLSPPWs [23] had been considered a significant way forward. In this scheme, a single-mode fiber is used to couple light into a polymer waveguide of dimension similar to the fiber core that eventually tapers down to a size comparable to that of DLSPPWs and butt couple the light into it. Although these schemes were reported to be quite efficient, the coupling efficiency significantly depends on the quality of facet of the chip and hence the dicing of the chip becomes very crucial. An alternative approach has been recently developed where a Si-based grating coupler is used to access the waveguides via an optical fiber from the top of the chip [34]. Figure 2b represents the picture of the grating coupler employed in the chip; the efficiency plot of the grating coupler is presented in Fig. 2c. A detailed investigation of such gratings is done by Gili de Villasante et al. [39] to provide efficient coupling of TM-polarized light in and out of the Si waveguides. These results demonstrate that the DLSPPWs can be efficiently interfaced with a Si-based optical system fabricated on a SOI chip and hence combine the advantages of plasmonics and low-loss Si photonics.

3. Power monitoring in DLSPPWs

The possibility of transmitting optical and electrical signals in the same component of plasmonic waveguides opens up interesting functionalities such as power monitoring of the DLSPPW mode. Power monitoring is realized via measuring variations in the resistance of metal stripes supporting a DLSPPW ridge caused by heating due to mode absorption. In this way, the inevitable propagation losses in plasmonic waveguides are turned into a useful functionality. To monitor changes in the DLSPPW gold stripe resistance the Wheatstone bridge configuration is used as depicted in Fig. 3a. All the four arms of the Wheatstone bridge have exactly the same configuration, making it a perfectly balanced bridge. For such a perfectly balanced bridge, any subsequent change in the resistance of one arm (due to mode absorption) is reflected in terms of the signal voltage of the bridge. The responsivity of the power monitor is hence defined as the change in signal voltage of the bridge as a function of input optical power to the DLSPPW arm. Power monitoring was first demonstrated for the case of long-range SPP waveguides [40] and subsequently for PMMA-loaded DLSPPWs [41]. For the latter case, a PMMA ridge of dimensions 1 μm × 1 μm was deposited on a thin gold layer supported by an MgF2 substrate of 750 μm thickness. The responsivity was measured in the range of 1.0–1.8 μV/μW. The main limiting factor in this case was the high thermal conductivity of MgF2 substrate (130 times larger than PMMA) that caused most of the heat to be dissipated into the substrate rather than being contained in the PMMA ridge.

An alternative approach where a 1.7-μm thick Cytop substrate deposited on the silica wafer with polymer loading of 1-μm wide and 0.6-μm thick Cyclomer ridge has shown considerable improvement in the responsivity of the power monitor. The responsivity of the power monitor with Cytop...
substrate was found to be at least 3.5 times higher even for a 4 times smaller bias voltage of the bridge. Figures 3d and e depict the responsivity and frequency response of a Cytop-based DLSPPW power monitor respectively. There is also a significant improvement in the frequency response mainly owing to balanced thermal distributions in the modified configuration of DLSPPW.

4. Data transmission through DLSPPW structures

Along with heterointegration of DLSPPWs with a standard SOI platform, various other functionalities such as static operation of electro-optic and thermo-optic switches based on DLSPPWs have been demonstrated [42–44]. However, the most important step towards the employment of plasmonic technology for true data application requires the ability of plasmonic structures to sustain high-speed data transmission. Wavelength division multiplexed (WDM) data transmission capabilities of plasmonic structures were initially tested using a 60-μm long PMMA-loaded DLSPPW by Giannoulis et al. [35]. In this very first demonstration, transmission of a 10-Gb/s non-return-to-zero signal through a DLSPPW showed error-free operation with negligible power penalty, hence denoting the strong potential of Si plasmonics towards actual datacom applications.

This capability was further strengthened by using the demonstration of 480-Gb/s WDM data transmission the same hybrid straight DLSPP waveguide [45]. The basic experimental setup for WDM transmission measurement and switching applications is demonstrated in Fig. 4a with the schematic of input and output stages along with the picture of a real Si-plasmonics hybrid chip in the center. In and out coupling fibers are also seen in the picture. For the WDM transmission through 60-μm long DLSPPWs, the source consisted of twelve distributed feedback (DFB) lasers emitting CW light beams spaced by 200 GHz within the 1542–1560 nm wavelength band. An arrayed waveguide grating (AWG) and 3-dB couplers were used to multiplex the twelve wavelengths into a single optical fiber and a Ti:LiNbO$_3$ Mach–Zehnder modulator (MZM) driven by a 40-Gb/s $2^{31}-1$ pseudorandom bit sequence (PRBS) was employed to encode the multiplexed signal into a 40-Gb/s

Figure 4 (a) WDM experimental setup with schematic of input and output stage and picture of the hybrid Si-plasmonics chip on the probe station. (b) 12 × 40-Gb/s signal entering the waveguide. (c) 12-channel spectrum after being amplified in the receiver’s EDFA. BER curves and eye diagrams for (d) best-performing channel (ch #1) and (e) worst-performing channel (ch #8).
NRZ data stream. A high-power erbium-doped fiber amplifier (EDFA) boosted the incoming WDM data signal, providing 24 dBm output power. A polarization controller was placed just before the hybrid chip to ensure TM-polarization conditions for the input light, as supported by plasmonic elements. The output of the hybrid waveguide, a multiwavelength data stream was then amplified by a low-noise EDFA and demultiplexed into its constituent data channels by an optical bandpass tunable filter (OBPF). Subsequently, each channel was detected by a 40-GHz 3-dB bandwidth photoreceiver followed by a 1:4 electrical demultiplexer in order to be received by a 10-Gb/s error detector for bit error rate (BER) measurements. Transmission losses of these 60-μm long DLSPP waveguide were found be to 11 dB at 1545 nm for TM-polarized light, which includes 6 dB of transmission loss, based on a cut-back measurement and 2.5 dB coupling loss per Si-to-DLSPP interface. The total fiber-to-fiber loss, however, was found to be wavelength dependent and ranged between 40 dB and 48 dB within the 12-channel spectral region. These high losses were mainly because of the TM grating coupler employed at both ends of the chip interface, which had a loss of 12 dB each at 1545 nm. The propagation loss of the Si waveguide part was found to be 4.6 dB/cm. The WDM signal after the chip was fed into a low-noise EDFA and demultiplexed into its constituent data channels. Figures 4b and c show the spectrum of a 12-channel data signal just before the input of the Si-plasmonics chip and after being amplified by the EDFA at the output stage, respectively.

Six out of twelve channels showed error-free operation with their power penalty against back-to-back (B2B) measurement ranging between 0.2 and 1 dB for a bit error rate (BER) value of $10^{-9}$, depending upon the spectral position of each specific channel with respect to the TM grating coupler spectral response and the amplification curve of the EDFAs. The remaining six channels (#6–11) exhibited an error floor at $\sim10^{-7}$ BER. Figures 4d and e depict the best (ch#1) and worst (ch#8) channels. It should be noted that the response of the 6 worst performing channels could have, in principle, been improved by demultiplexing the output of the chip before amplification but it was prohibited by the low output power per channel, which was insufficient for the preamplification stage. This situation can be avoided by using a low-loss TM grating coupler to facilitate more efficient in and out coupling.

5. DLSPPW-based switching elements

The next step towards practical plasmonic circuits is demonstration of WDM switching. In this direction, the first demonstration of single-channel WDM switching at 10 Gb/s was reported using a DLSPPW-based asymmetric Mach–Zehnder interferometer (A-MZI) structure [46]. The A-MZI structure used for switching experiments is schematically presented in Fig. 5a. It consists of two DLSPPWs as its active, electrically controlled branches that are incorporated between two silicon coupler stages. The upper
plasmonic arm of the A-MZI has a length of $L_1 = 60 \, \mu m$ and a PMMA ridge cross section with $W_1 = 500 \, nm$ width and 600 nm height. The lower plasmonic arm has again a total length of 60 $\mu m$ and identical PMMA ridge dimensions, employing, however, a $L_2 = 6-\mu m$ long DLSPPW section that is widened from $W_1$ to $W_2 = 700 \, nm$ [47]. This widened DLSPPW section introduces a default phase asymmetry of $\pi/2$ between the two MZI arms, taking advantage of the higher effective refractive-index value experienced by the DLSPPW mode in the PMMA ridge. The switching operation is obtained upon applying an electric current to one of the two A-MZI plasmonic branches, enforcing a temperature change in the DLSPPW and consequently a phase shift due to the thermo-optic effect [1]. By electrically controlling the upper A-MZI arm, a negative phase shift is experienced by the propagating DLSPPW mode as a result of the negative thermo-optic coefficient (TOC) of the PMMA that equals $-1.05 \times 10^{-4} \, K^{-1}$. When the induced phase shift equals $\pi/2$, the phase difference between the modes travelling through the two MZI branches equals $\pi$, and therefore the whole mode power is exported to the BAR output of the device. On the contrary, when the same current level applies only to the lower MZI plasmonic branch, the default MZI phase asymmetry is cancelled out due to the $-\pi/2$ thermo-optically induced phase shift and, consequently, the whole mode power emerges at the CROSS port of the interferometer.

To evaluate the switching performance of the Si-plasmonics A-MZI, first the static measurements were performed followed by dynamic as well as with four-channel WDM data measurements. Fig. 5b depicts the static thermo-optic transfer function for the CROSS and BAR port of the A-MZI. This was obtained by launching a continuous wave (CW) beam of 1542 nm directly into the A-MZI and simultaneously applying a direct current (DC) to the upper arm of the MZI. It should be specifically highlighted that the DC control signal is applied to the same metal layer that supports the DLSPP waveguide structure. An application of 40 mA of DC current resulted in extinction ratio (ER) of 14 dB and 0.9 dB for the CROSS and BAR port, respectively. The poor ER value of the BAR port is attributed to 95:5, instead of 50:50 silicon input and output coupler of MZI because of a design error. A theoretical output power transfer function for a MZI equipped with a 95:5 coupler was then calculated to compare it with the experimentally obtained transfer function. It was revealed (Fig. 5c) that the initial phase biasing point of A-MZI is at approximately 70° instead of the originally intended $\pi/2$. The injection of 40 mA of current to the upper arm of MZI caused a thermo-optically induced phase shift of $\sim -90°$, leading to a total phase difference of 160° between the two arms of the MZI. The resistance of the 60- $\mu m$ long plasmonic A-MZI branch was found to be 6.8 $\Omega$ at the 0 mA current level, rising to 8.2 $\Omega$ for a DC current of 40 mA due to the temperature-dependent gold resistivity. Therefore, the consumed power for a 40-mA driving current was $\sim 13.1 \, mW$.

For the dynamic response of the A-MZI switch, an electrical rectangular pulse (red dotted line in Fig. 5d) of 35 $\mu$s duration and repetition rate of 20 kHz and a nominal electric current peak value of 40 mA was applied to the upper arm of the A-MZI. Figures 5d and e show the dynamic response of BAR and CROSS port with 9% and 96% modulation depth, respectively. The rise and fall time were also measured at the CROSS port to be $3.8 \, \mu s$ and $2.3 \, \mu s$, respectively, as shown in the corresponding inset. The fall time of $2.3 \, \mu s$ corresponds to the time required for the plasmonic waveguide to cool down.

The multichannel WDM experimental setup for A-MZI switches consisted of four DFB lasers emitting at 1545.1, 1546.7, 1547.7 and 1549.1 nm, respectively, used as the four transmitter channels in the WDM switching experimental setup. The four CW signals were initially multiplexed using fiber 3-dB couplers and modulated in pairs (channels 1 and 3 together and channels 2 and 4 forming another pair) by two Ti:LiNbO$_3$ MZM driven by 10-Gb/s data and data bar outputs of the MP1763C Anritsu pattern generator. In this way, four 10-Gb/s $2^{21}–1$ NRZ data sequences were generated with channels 1–3 and channels 2–4 carrying decorrelated signals. All four channels were subsequently combined into the same optical link via a fiber 3-dB coupler. The multiwavelength data signal was then amplified by a high-power EDFA providing 31-dBm output power before being fed into the A-MZI. A SRS DG535 digital delay/pulse generator operating at 20 kHz controlled dynamically the switching state of the MZI based on the thermal-optic effect. The multichannel signal that was received at the MZI’s output was amplified by a two-stage EDFA (EDFA2 with $-15 \, dBm$ output power for an input power of $-22 \, dBm$ and EDFA3) that included a 5-nm OBPF between the two stages for noise rejection. The WDM signal was demultiplexed into its constituent wavelengths through a narrow OBPF (0.8 nm). Each data channel was then split and launched concurrently into a 30-GHz HP 83480A sampling oscilloscope and a 10-GHz 3-dB bandwidth DSC-R402PIN photoreceiver that was connected to a 10-Gb/s MP1764C Anritsu error detector. The 10-GHz reference signal for the transmitter and the receiver was provided by a 20-GHz MG3692B Anritsu signal generator.

Figure 5f represents the 4-channel WDM signal before entering the A-MZI. It should be noted that the presented curve is only a small fraction of total power that was fed to the A-MZI. The unequal power profile of WDM signal is mainly due to the nonflattened response of the EDFA amplifying the signal before A-MZI. The output of A-MZI after being amplified by the EDFA is represented in Fig. 5g, it can be noted that the response of the MZI has a clear wavelength dependence with transmission loss increasing by 3 dB when moving from 1546 nm to 1550 nm, mainly originating from the spectral response of the TM grating coupler at the input and output of A-MZI. The control signal for the switching experiment had a repetition rate of 20 kHz, with rectangular pulses of 15 $\mu$s duration and an electric current peak value of 40 mA. Successful operation of the device was obtained for all the four channels, revealing again inverted mode operation at the CROSS port, similar to that obtained for the dynamic response, with an ER value close to 14 dB. The BAR output port had again a poor ER...
6. Demonstration of Cyclomer-loaded switches

To improve the performance of DLSPP-based switches, two important approaches have been identified; a new polymer with a higher TOC than that of PMMA and new active structures [45, 48]. In this direction, another set of active plasmonic structures that have been employed for switching demonstration are DLSPPW-based thermo-optic dual resonators. These resonators comprise of Cyclomer-loaded dual racetrack resonators placed diagonally in a nonsymmetric orientation in a cross configuration (Fig. 6a). The image’s inset reveals the adequate quality of the DLSPP structures with the Cyclomer-loaded waveguides exhibiting a nearly square 600 × 500 nm² cross section, allowing for a gap resolution of 300 nm between the intersecting waveguides and the racetrack resonators. Cyclomer is a promising alternative to PMMA, mainly owing to its high TOC ~ −2.8 × 10⁻⁴ K⁻¹ and its ease to process submicrometer dimensions for the waveguide fabrication [48]. Each Cyclomer-loaded racetrack resonator has a radius of 5 μm and two straight interaction lengths of L₁ = 2 μm and L₄ = 0 μm, respectively, while the gaps between the intersecting waveguides and the racetrack resonators are approximately 300 nm. For thermo-optic experiments, the sample was heated by connecting the underlying gold film to a current source and the variation in temperature was monitored by a microthermocouple residing on the gold surface. A maximum current of 400 mA was applied to facilitate the heating.

The optical characterization of the Cyclomer-loaded dual racetrack resonators was performed by LRM. As pointed out earlier, the SPP mode propagating along a DLSPPW waveguide is in essence a leaky mode in that it radiates a fraction of its energy within the dielectric substrate. The radiation channel for the damping of the SPP mode can be controlled by carefully adjusting the thickness of the metal film. The excitation of the input waveguides of the resonators is achieved by focusing the incident laser (tunable from 1500 to 1600 nm) on one end of the input waveguides using a ×100 microscope objective. Since the effective index of the DLSPPW mode is lower than the reflective index of the glass substrate, the plasmon mode is leaky within the substrate. The radiation leakages of this mode can be detected by means of an immersion oil objective (numerical aperture = 1.49) and the image of the resonator can be formed onto the detector of a highly sensitive near-infrared charged coupled device (CCD) camera. The input and output power are obtained by integrating the intensity within the respective areas. By monitoring these powers over the entire tuning range of the laser, the transmission spectra of the resonators are obtained.

LRM was employed to record the spectral response of the structure. Figures 6b and c show the LRM image of the structure for “Cool” and “Hot” states, respectively. The “Cool” state corresponds to the case when there is no heating of the structure (room temperature), whereas the “Hot” state is achieved by injecting a DC current of value 400 mA leading to a temperature change of 60 ±5°C. Complete switching is clearly observed in the device with output at its Through-port for the “Cool” state and at the Drop-port for the “Hot” state.

The transmission spectra of the Cyclomer-loaded dual-resonator switch for both the Through and Drop output ports are shown in Figs. 6d and e, respectively, when SPPs are excited at In#1 port according to Fig. 6a. A clear resonant behavior can be observed with the free spectral range (FSR) of the Through-port resonances being equal to 38 nm. When operating in unheated conditions, the resonant dips at the Through-port have an extinction ratio (ER) of more than 35 dB, while the corresponding ER value for the Drop-port resonant peak is close to 10 dB in the 1560–1580 nm spectral region. Insertion losses for the Through and Drop ports were measured to be −10 dB and −8 dB, respectively. The propagation loss factor of the DLSPP waveguide was also measured to be 0.1 dB/μm, which is consistent with previous measurements of Si-DLSPP heterointegrated structures. It should also be mentioned that ER values of higher than 6 dB were obtained over a 6-nm spectral range around 1558 nm for both output ports, confirming the broadband switching characteristics of this switch can allow in principle for simultaneous switching of six 100-GHz-spaced WDM channels. High ER values at both the output ports simultaneously highlight the improved performance because of the Cyclomer loading of DLSPP waveguides [35]. It should also be pointed out here that high current requirement was mainly due to large gold layer supporting the

---

**Figure 6** (a) SEM image of the dual-resonator Cyclomer DLSPPW switch, (b) LRM image in (b) “Cool” and (c) “Hot” states at λ = 1558 nm. (d) Transmission spectra for the Through-port in the “Cool” and the “Hot” state. (e) Transmission spectra for the Drop-port in the “Cool” and the “Hot” state.
whole structure. This can be significantly reduced once the plasmonic structures are heterointegrated with Si waveguides on SOI platform.

7. Long-range dielectric-loaded surface plasmon polariton waveguides

In the pursuit of improving the performance of DLSP-PWs, a new class of waveguides has recently emerged called long-range DLSP waveguides. This new waveguide architecture enables guiding of an SPP mode over mm-long distances, while still retaining relatively strong mode confinement [49, 50]. The schematic layout of LR-DLSP waveguide structure is shown in Fig. 7a. The inset of the figure represents the tightly confined modal distribution of LR-DLSP waveguides. These waveguides are fabricated by spinning a 255-nm thick layer of high refractive index UV-curable organic–inorganic hybrid material (Ormoclear) onto a 4-μm thick Cytop-coated silicon wafer. Straight and bent 500-nm wide and 15-nm thick gold stripes were patterned by EBL, metal evaporation and lift-off. The waveguide fabrication was completed by the second step of EBL for patterning 1-μm thick and wide ridge of PMMA on top of the gold [51]. Straight and bent LR-DLSPPWs (Figs. 7b and c) were fabricated to investigate the modal and propagation characteristics of LR-DLSPPWs.

The fabricated LR-DLSPPWs were cleaved from one end of the sample to facilitate butt coupling, whereas the other end of the waveguide was incorporated with a grating of period ~750 nm. The purpose of this grating was to monitor the LR-DLSPPW excitation by observing scattering out of the surface plane by the grating at the waveguide termination. These waveguides were characterized by SNOM arrangements, which consisted of an uncoated fiber probe and an arrangement for end-fire coupling tunable (1425–1545 nm) TM-polarized (electric field perpendicular to the sample surface plane) radiation into the LR-DLSPPW through a tapered-lensed polarization-maintaining single-mode fiber. The adjustment of the incoupling fiber was accomplished while monitoring the light propagation along the waveguide with the help of a far-field microscope arrangement. Following the far-field adjustment, the arrangement was moved under the SNOM head to map the intensity distribution in the waveguide structure under investigation by the uncoated sharp fiber tip of SNOM. The tip was scanned along the waveguide at a constant distance of a few nanometers maintained by shear-force feedback, and the radiation collected by the fiber was detected with a femtowatt InGaAs photodetector. The near-field images were recorded at a distance of ~80 μm from the incoupling waveguide edge to decrease the influence of stray light.

The two SNOM images of straight waveguides shown in Fig. 7d are also very typical for short (1425–1450 nm) and long (1525–1545 nm) wavelengths. The SNOM images are similar to those obtained with DL-SPPWs [52] featuring efficient mode confinement (in the lateral cross section) within the ridge area and intensity variations along the propagation direction. The propagation length estimated from the decay curve is found to increase linearly with increasing wavelength, reaching ~520 μm for λ ≈ 1545 nm, which is very large compared to that of DLSPPWs (~50 μm) but still significantly lower than the propagation length of ~3 mm expected at λ ≈ 1555 nm from numerical simulations [49, 50]. The discrepancy can be explained partly by leakage radiation losses into the Si substrate due to a finite thickness of a low-index Cytop layer and scattering losses from structural defects in the PMMA ridge and gold stripe, all of which were not included in calculations.

The confinement of the LR-DLSPPW modes was further investigated by characterizing abruptly bent waveguides as well as S-bend structures. The SNOM image in Fig. 7e demonstrates efficient and well-confined LR-DLSPPW mode propagation through the bend. The

Figure 7 (a) Schematic layout for the cross section of the fabricated LR-DLSPPW structure. The inset represents the modal structure of the fundamental LR-DLSPPW mode calculated at λ = 1550 nm. Optical microscopy image of (b) straight and (c) S-bent waveguide. (d–f) Near-field optical images of (d) straight waveguides taken at λ ≈ 1450 nm (left) and 1525 nm (right), and of (e) abrupt and (f) S-bent waveguides.
possibility of realizing a compact and efficient S-bend structure was also explored (Fig. 7c) by designing an S-bend based on sine curves allowing an adiabatic modification of LR-DLSPPW mode throughout the bend. Figure 7f demonstrates the excellent performance of the S-bend with an overall loss of about 1.8 dB. The fact that the LRDLSPPW mode can be well confined to the subwavelength cross section and guided with low propagation loss (lower than most of the SPP waveguides) holds promise for complex highly integrated plasmonic circuits, whose performance could be even better than that demonstrated with DLSPPWs.

8. Discussion

Two very important parameters that affect the performance of thermo-optic based switches are power consumption and response time. In the case of DLSPPW-based switches, it should also be noted that the amount of temperature increase that causes the thermo-optic effect is limited by the properties of the dielectric loading of the DLSPPWs. In this regard, the performance of a DLSPPW-based thermo-optic switch is also affected by the thermal properties of the buffer layer, i.e. the layer beneath a metal strip. Figure 8 presents a comparative study of two commonly used buffer layers in the present context, Cytop and SiO$_2$, which was conducted by using numerical simulations of heat dissipation when heating the metal strip, shown schematically in Fig. 8b. During the thermo-optic operation, passage of an electric current through the metal (gold) strip causes a dissipation of electrical energy to thermal energy by ohmic heating, which is then transferred to any material in contact with the gold strip electrode through conductive heating. The amount of heat transferred to the ridge (which actually leads to thermo-optically induced phase shift) depends upon the thermal conductivity of ridge material and the material below the gold electrode contact area as well as the ridge cross section and the buffer layer thickness and material. A buffer layer with a lower thermal conductivity or higher thermal resistance requires a lower power to increase its temperature and consequently the temperature of the polymer ridge on the top of gold. However, the lower thermal conductivity of the buffer layer also implies that it takes a longer time to increase the temperature of the ridge, hence affecting the response time of the thermo-optic switch.

In fact, the metric of power consumption × time response has been commonly used for the comparison of TO switching elements in application where both low power requirement and fast response time are prerequisites for high performance [53]. There have been many demonstrations of efficient TO switching configuration recently both based on SOI as well as polymer-based active waveguide platforms. One of the first experimental demonstrations of an SOI-based TO switch was by Espinola et al. [54] where a SOI-based MZI was demonstrated to have a power consumption of 50 mW and rise time of 3.5 μs. It was later demonstrated that the power requirement can be significantly reduced by considering a free-standing Si waveguide geometry. Sub-milliwatt power (as low as 0.49 mW) consumption was reported, but at the cost of a high response time [55,56]. The smallest response time (2.8 μs) among the single-driving SOI-based thermo-optic switches has been achieved by using integrated NiSi waveguide heaters, having, however, a power consumption of 20 mW [57]. Polymers, which provide a better thermo-optic coefficient, have also been subjected to intensive consideration for TO switches. Although polymer-based TO switches can lead to very low energy requirements they suffer from high response times [53,58]. In this context, plasmonics-based TO switches offer great advantage in terms of power consumption–time product [47]. The A-MZI switch discussed here offers the smallest active region length as well as low power requirement (13 mW) and a fast response time (3.8 μs), and consequently the lowest power consumption-time response product compared to all the schemes discussed above. The low power consumption comes from its asymmetric arrangement as well as inherent DLSPP waveguide characteristics. The asymmetric arrangement requires only a π/2 thermo-optically induced phase shift, as opposed to a π

Figure 8 (a) Schematic of DLSPPW cross section (b) schematic of the arrangement for theoretical consideration. (c) Simulations of the effect of buffer layer material and its thickness in terms of rise time and dissipated power.
phase shift in regular MZI designs. A similar idea was implemented in [59], where a folded Si waveguide were used to increase the overall phase difference between the two arms of MZI, although this shows quite a significant improvement it is limited by complicated fabrication process. Another advantage plasmonics-based TO switches offer is in terms of waveguide geometry, which requires the metal to be an inherent part of DLSPPW, thus bringing the metallic film directly attached to the dielectric loading and, more specifically, at the site of mode intensity maximum. With this configuration, it is possible to apply electrical signals to the same metal film that carries the plasmonic mode of DLSPP waveguides, thus allowing seamless integration of electronics and optics onto the same metal circuitry. This allows for efficiently transferring the heat to the dielectric loading, reducing the power consumption significantly. It also takes advantage of the rapid thermo-optic response time of the metal in order to yield low switching time values. SOI-based devices, on the other hand, cannot deliver this advantage since separate elements are usually used as heaters located at certain distances from the Si waveguide core.

In conclusion, this article addresses current prospects in the developments of plasmonic waveguide-based components towards real practical applications by discussing the critical requirements of heterointegration of DLSPPWs with SOI platforms and their applicability in true data traffic conditions as well as active circuitry. Power monitoring presents added functionality of DLSPP waveguides that are accompanied with inherent ohmic loss because of the metal. Demonstration of WDM transmission of 0.48 Tbps aggregate traffic through SOI-integrated DLSPPWs along with WDM switching using a DLSPP-based A-MZI device provides a very positive perspective for plasmonic waveguide-based components for true datacom and telecom traffic applications. The direction towards the reduction of power consumption, footprint and losses has been identified by demonstrating the use of Cyclomer instead of PMMA as the polymer loading of DLSPPWs. The use of Cyclomer, which has a three times higher thermo-optic coefficient compared to PMMA for DLSPPW-based active switches will reduce the power consumption as well as the footprint very significantly. The role of the buffer layer is also discussed as an important factor affecting the performance of DLSPP-based thermo-optic switches. The impressive progress achieved during recent years with DLSPPW-based components and their usage for data communication systems as well as new developments resulting in demonstration of LR-DLSPPWs pave the way for future endeavors for the dielectric-loaded plasmonic technology platform.

Acknowledgments. This work was supported by the European Union project FP7 ICT-PLATON (ICT-STREP no. 249135) and by the Danish Council for Independent Research project ANAP (contract no. 09-072949).

Received: 3 December 2012, Revised: 23 January 2013, Accepted: 24 January 2013
Published online: 28 February 2013

Key words: Active plasmonics, modulation, switching, telecommunications.

Ashwani Kumar received the M.Sc. degree in physics from the Indian Institute of Technology, Delhi, India, in 2006, and the Ph.D. degree in active plasmonics from, Nanyang Technological University, Singapore, in 2010. His current research interests include the fundamental studies of surface plasmon-polariton waveguides and integration of plasmonics with silicon platform for optical interconnect applications.

Jacek Gosciniak received the M.Sc. degree in technical physics from Technical University of Lodz, Lodz, Poland, in 2002. In 2008 he commenced Ph.D. program in Macquarie University, Australia in the field of plasmonics as well as he was a member of the CUDOS research program. In 2009 he moved to Sergey Bozhevolnyi group in University of Southern Denmark where he is now working towards the Ph.D. degree in the SENSE department.

Valentyn S. Volkov, born in 1977, is an Associate Professor at the Institute of Technology and Innovation (ITI), University of Southern Denmark. He received the M.Sc. degree (in Physics) in 2000 from Moscow State University (Russia) and obtained his Ph. D. in 2003 from Aalborg University (Denmark). From 2003 to 2008 he was a postdoctoral researcher at the Department of Physics and Nanotechnology, Aalborg University (Denmark). His research is focused on the use and development of near-field scanning optical microscopy for integrated optics applications.

Sotirios Papaioannou received the Diploma degree in electrical and computer engineering from the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, and the M.Sc. degree in computer science from the Department of Informatics, Aristotle University of Thessaloniki, in 2008 and 2010, respectively. He is currently pursuing the Ph.D. degree with the Department of Informatics, Aristotle University of Thessaloniki. His current research interests include analysis, design and simulation of photonic circuits, and systems for high-speed optical interconnects.

Dimitrios Kalavrouziotis received the Diploma degree in electrical and computer engineering from the National Technical University of Athens, Greece, in 2009. His current research interests include the exploitation of plasmonics in chip-scale data communication for optical interconnects.

Konstantinos Vyrskinos received the B.Sc. degree in physics from the Aristotle University of Thessaloniki, Greece, in 2001, and the Ph.D. degree from the Electrical and Computer Engineering Department, National Technical University of Athens, Greece, in 2007. His current research interests include silicon nanophotonic and plasmonic technology.

Jean-Claude Weeber received the Ph.D. degree in physics from the University of Burgundy, Dijon, France, in 1996. He is currently with the Institut Carnot de Bourgogne, Unite Mixte de Recherche Conseil National de la Recherche Scientifique.
Karim Hassan was born in Troyes in 1987. He received the B.Sc. degree in physics in 2008, and the M.Sc. degree in Nanotechnologies and Nanobiosciences in 2010, both from the University of Burgundy, Dijon, France. Part of his M.Sc. formation was a 6-month internship at the Optique Submicronique NanoCapteurs (OSNC) group in Dijon, France, where he work on the fabrication and characterization of thermo-optic plasmon devices. He is currently working toward his Ph.D. degree in physics at the OSNC group.

Laurent Markey received the engineering (MSc) degree from the Graduate School of Chemistry and Physics of Bordeaux, France in 1994 and the PhD in Materials Science from University of Lille, France in 1998 where he worked at the Institute of Electronics, Microelectronics and Nanotechnology. In 1999–2001, he worked in the Polymer Research Centre at the University of Surrey, UK. He then worked on advanced lithography processes for the semiconductor company STMicroelectronics, France, until 2002. He is currently in ICB Laboratory in Dijon at University of Burgundy, France, specializing in nanofabrication and microfabrication processes for various applications related to nanophotonics, plasmonics and nanosensors.

Alain Dereux, PhD in Physics (Univ. Namur, Belgium, 1991), was post-doc researcher at the IBM Zürich Research Lab. In 1995, he was appointed Professor at the Univ. of Burgundy (Dijon, France) where he was later promoted Full Professor. In 2012, he was nominated director of the Laboratoire Interdisciplinaire Carnot de Bourgogne – jointly operated by CNRS and the Univ. of Burgundy. A. Dereux’ research activities, covering near-field optics and surface plasmon photonics, aim at controlling optical processes at the sub-wavelength scale and are reported in more than 140 papers featuring above 7000 citations.

Tolga Tekin received the Ph.D. degree in electrical engineering and computer science from the Technical University of Berlin, Germany, in 2004. He is currently with the Research Center of Microperipheric Technologies, Technical University of Berlin, where he is engaged in microsystems, photonic-integrated system-in-package, photonic interconnects, and 3-D heterogeneous integration research activities. He is a Photonic and Plasmonic Systems Group Manager with Fraunhofer IZM.

Dr. Michael Waldow received his diploma in electrical engineering at University of Karlsruhe in 2006 on design of high-speed integrated 40Gb/s optical modulators. In 2005/2006 he was at Bell-Labs, Crawford Hills for an internship. After working for five years as a scientist at RWTH Aachen (2006–2011), he received his PhD in photonics (2011). Since 2011 he is leading the nanophotonic group at AMO GmbH. He has authored and co-authored several journal papers and conference proceedings.

Dimitrios Apostolopoulos received the Diploma degree in electrical and computer engineering and the Ph.D. degree from the National Technical University of Athens, Greece, in 2004 and 2009, respectively. His current research interests include photonic integration, optical interconnects, and all-optical bit storage circuits.

Hercules Avramopoulos received the B.Sc. degree in physics and the Ph.D. degree from the Imperial College of London, U.K. He is the head of Photonics Technology Research Laboratories in National Technical University of Athens, Greece. His research interests include pulse generation, amplification, and transmission in optical fibers and a large number of laser and amplifier systems for a variety of applications.

Nikos Pleros is a Faculty Member at the Department of Informatics, Aristotle University of Thessaloniki, Greece, since September 2007, currently serving as Assistant Professor. He obtained the Diploma and the PhD Degree in Electrical & Computer Engineering from the National Technical University of Athens (NTUA) in 2000 and 2004, respectively. His research interests include all aspects of optical communications and photonic systems spanning from integrated photonic devices to optical networking concepts.

Sergey I. Bozhevolnyi (M.Sc.’78, Ph.D.’81, Dr.Scient.’98) is Professor in Nano-Optics at the University of Southern Denmark (since 2008). During 2001–2004, he was also the Chief Technical Officer (CTO) of Micro Managed Photons A/S set up to commercialize plasmonic waveguides. His current research interests include linear and nonlinear nano-optics, surface plasmon polaritons, plasmonic waveguides and circuits, as well as integrated and fiber optics. He is a Fellow of the Optical Society of America.

References

[1] D. K. Gramotnev and S. I. Bozhevolnyi, Nature Photon. 4, 83–91 (2010).
[2] H. A. Atwater, Sci. Am. Mag. 296, 38–45 (2007).
[3] R. Zia, J. A. Schuller, A. Chandran, and M. L. Brongersma, Mater. Today 9, 20–27 (2006).
[4] A. V. Zayats, I. I. Smolyaninov, and A. A. Maradudin, Phys. Rep. 408, 311–314 (2005).
[5] J. M. Pitarke, V. M. Silkin, E. V. Chulkov, and P. M. Echenique, Rep. Prog. Phys. 70, 1–87 (2007).
[6] S. I. Bozhevolnyi, Plasmonic Nanoguides and Circuits, ed. S. I. Bozhevolnyi (Pan Stanford, Singapore, 2009).
[7] S. A. Maier, Plasmonics: Fundamentals and Applications (Springer, New York, 2007).
[8] E. N. Economou, Phys. Rev. 182, 539–54 (1969).
[9] D. Sarid, Phys. Rev. Lett. 47, 1927–30 (1981).
[10] A. Boltasseva, T. Nikolajsen, K. Leosson, K. Kjaer, M. S. Larsen, and S. I. Bozhevolnyi, J. Lightwave Technol. 23, 413–22 (2005).
[11] A. W. Sanders, D. A. Routenberg, B. J. Wiley, Y. Xia, E. R. Dufresne, and M. Reed, Nano Lett. 6, 1822–6 (2006).
[12] X.-W. Chen, V. Sandoghdar, and M. Agio, Nano Lett. 9, 3756–61 (2009).
[54] R. L. Espinola, M.-C. Tsai, J. T. Yardley and R. M. Osgood, IEEE Photon. Technol. Lett. 15, 1366–1368 (2003).
[55] Q. Fang, J. F. Song, T. Liow, H. Cai, M. B. Yu, G. Q. Lo, and D. Kwong, IEEE Photon. Technol. Lett. 23, 525–527 (2011).
[56] P. Sun and R. M. Reano, Opt. Exp. 18, 8406–8411 (2010).
[57] J. Van Campenhout, W. M. Green, S. Assefa, and Y. A. Vlasov, Opt. Lett. 35, 1013–1015 (2010).
[58] N. Xie, T. Hashimoto, and K. Utaka, IEEE Photon. Technol. Lett. 21, 1861–1863 (2009).
[59] A. Densmore, S. Janz, R. Ma, J. H. Schmid, D. X. Xu, A. Delâge, J. Lapointe, M. Vachon, and P. Cheben, Opt. Exp. 17, 10457–10465 (2009).