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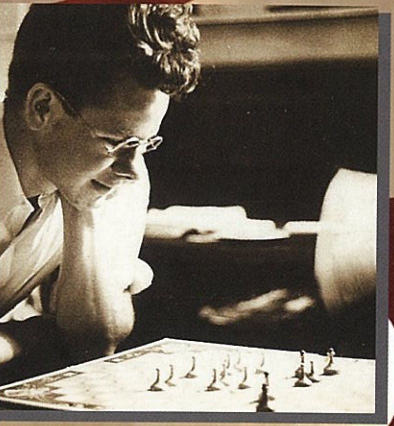

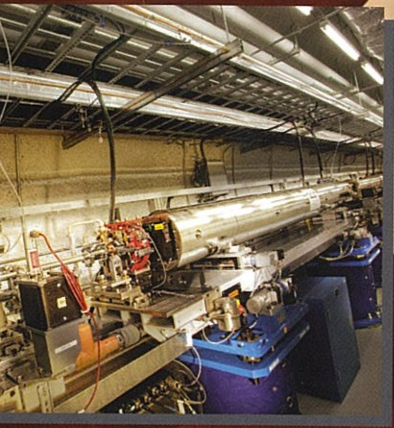

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Integrated Optical MicroSystems: Guiding Light into the Future

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Introduction

As we enter the 21st century, our society faces new challenges. On the one hand, recent years have seen the need for increasingly faster computers, for communication networks with larger data transmission capacity and for the integration of more functionality on a single chip. Current electronics alone will not be able to cope with these demands. Computers will require smaller transistors, which will soon reach their physical limit given by the atomic dimensions. Furthermore, as more transistors are integrated on a chip, the electrical wires that interconnect them will accordingly decrease in size, which augments their electrical resistance and therefore limits the amount of information (or bandwidth) that they can carry. Integration of more functionality on a chip will pose many stringent requirements on the inter-chip connections.

On the other hand, in our aging society, longer life expectancy implies that coming years will see an increase on the fraction of the population over the age of sixty. Radical approaches should be applied to healthcare, moving from the current treatment of the disease towards prevention and diagnostics at the earliest possible stage. Cheap, portable and non-invasive diagnostic tools are fundamental to maintain the quality of life of an increasing number of elderly people. Finally, monitoring the evolution of our fragile environment and ensuring the well-being of our scarce resources will permit to preserve our planet for future generations.

Integrated optics is a key enabling technology that can potentially help to overcome the aforementioned bottlenecks. Several decades ago, optical fibers revolutionized the communication field, providing affordable connectivity between people in different parts of the world. A prime example is the widespread of high-speed internet and mobile communications which, together with the advent of social networks, have changed the global human communication behavior. Integrated waveguides are on-chip versions of optical fibers. First proposed in the 1960's, integrated optical circuits are analogous to electronic integrated circuits. The main difference is that the information is processed in the form of "light" instead of by electrical signals, being therefore capable of much higher transmission speed and processing capabilities. By selecting the correct set of materials, waveguides that confine and route light with dimensions in the micrometer range can be integrated on a chip. Novel integrated waveguide technologies, such as the ones based on plasmonic propagation, will permit confining the light to even smaller dimensions, bridging the gap with the size of photonic and electronic integrated circuits. The high bandwidth and the high transmission capacity, together with their compatibility with current electronic circuitry, could make integrated photonic devices the next stepping stone that will permit to address the challenges faced by current technologies.

At the Integrated Optical Microsystems (IOMS) Group of the University of Twente, we are working towards setting the basis for the future of on-chip nanophotonics. In the following sections, our work on on-chip lasers and amplifiers, optical waveguide devices for different applications such as medical imaging and sensing as well as photonics-electronics integration technologies will be detailed [1].

On-chip Integrated Lasers and Amplifiers

On-chip waveguide lasers are of particular importance for the realization of compact, robust and reliable optical devices, since the entire laser cavity along with the optical feedback elements can be fabricated on the same chip. Besides, when an application requires a laser array, e.g., for simultaneous operation over a specific wavelength range, an on-chip integrated approach is advantageous in terms of size, cost and power consumption. In recent years, a great deal of effort has been directed towards the realization of on-chip lasers and

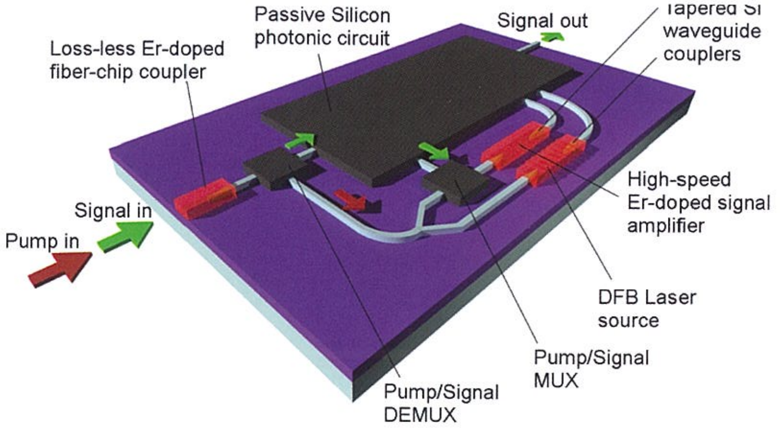


figure 1: illustration of an advanced integrated photonic circuit with amplification of existing signal light and additional signal light generated by miniature Er-doped distributed feedback (DFB) waveguide

their integration on a silicon platform.

At the Integrated Optical Micro-Systems (IOMS) group, we use rare-earth-ion-doped dielectric materials to realize active photonic waveguide circuits integrated on a single chip. The main advantages of rare-earth doped materials are the narrow linewidths achievable as well as very good gain properties, permitting the amplification of high-rate optical signals without distortion. Fig. 1 shows an example that includes distributed-feedback waveguide laser sources and high-speed erbium-doped amplifiers.

Many materials can be used as hosts for rare-earth ions. One of them is aluminum oxide (Al_2O_3), which can be easily deposited on different substrates, enabling its integration with other photonic devices. Its relatively high refractive index (1.67 at 1.55 µm wavelength) compared to other glasses permits the fabrication of small waveguides with tight bends, minimizing the device footprint. Typical optical gain achieved is around 2 dB/cm, which means that a device length of 1.5 cm is required to double (+3 dB) the optical signal intensity. Other very interesting hosts for rare-earth ions are crystalline materials belonging to the family of double tungstates, $KY(WO_4)_2$, $KLu(WO_4)_2$ and $KGd(WO_4)_2$. These materials are grown as thin crystalline layers by a relatively low-cost and efficient technique called liquid-phase epitaxy (LPE). We have demonstrated a very high gain per unit length, ~950 dB/cm, in Yb^{3+}-doped $KGd_{1-x}Lu_x(WO_4)_2$. Such gain will permit doubling the intensity of the optical signal in a device length of 30 µm, therefore appearing as a very promising material for nano-photonic devices. Finally, when low-cost lasers and amplifiers are required, polymers could be used as the host material. Typical problems with polymer host materials are the lower stability of the material under high light intensities and the fluorescence quenching due to the high energy vibration of the O-H and C-H bonds. By proper selection of the polymer composition, we have demonstrated both amplification and lasing from a Nd^{3+}-doped polymer waveguide emitting at 1060 nm.

The narrow linewidths achieved in the lasers based on rare-earth materials (in the kHz regime) make them enabling elements for applications such as the photonic generation of microwave signals (microwave photonics), optical coherent communications (telecommunications), swept-source OCT (medical imaging) and optical clock generation, just to mention a few. A narrow-linewidth monolithic erbium-doped waveguide laser operating at a wavelength of 1.55 µm, with a coherence length of more than 55 km has been recently demonstrated at the IOMS group and will be used for the photonic generation of microwave signals.

Integrated optics for optical imaging and sensing

Among the different waveguide technologies available for the integration of sensing and imaging devices on a chip, the IOMS Group has focused on silicon oxynitride (SiON), since it is transparent over a broad wavelength range and presents a tunable refractive index from 1.45 to 2, permitting devices with small footprint to be fabricated. This technology has been applied to the miniaturization of OCT systems for optical imaging, Raman spectroscopy on a chip and sensing devices for the detection of various analytes. Optical waveguides can also be combined with microfluidic channels to achieve a complete miniaturization on a chip.

OCT is an interferometric imaging technique which has the ability to generate high-resolution cross-sectional images of biological tissue up to a depth of a few millimeters. Nowadays OCT is used commonly in the clinic, particularly in ophthalmology. Current state-of-the-art OCT systems are Fourier-domain systems based on either a spectral-domain (SD, using a spectrometer) or swept-source (SS, using a rapidly tunable laser) system design. These systems consist of a multitude of fiber and free-space optical components which make them costly and bulky. The size and cost of an OCT system can be decreased significantly through the use of integrated optics.

Our research is currently aiming to the design of an on-chip SD-OCT system in SiON, which is transparent over the OCT wavelength bands at 800, 1000, and 1300 nm. One of the key components of a SD-OCT system is the high-resolution spectrometer, which is also the most challenging part to integrate on a chip. Arrayed-waveguide gratings (AWGs) are commonly used for wavelength demultiplexing in the telecommunication field, offering high resolution over a small bandwidth. AWGs are also excellent candidates for large-bandwidth applications, such as OCT and spectroscopy. An AWG consists of input/output waveguides, two free-propagation regions and a phased array of multiple waveguides with a constant path-length difference between neighboring waveguides.

In our group, we have successfully designed; fabricated and characterized SiON-based AWG spectrometers as a first miniaturizing step of an SD-OCT system. Their wavelength resolution (0.4 nm) and free spectral range (78 nm) have been determined by the OCT axial resolution (18.5 µm) and depth range (1 mm) requirements. In collaboration with the Amsterdam Medical Center, we have performed OCT imaging by using a fiber-based OCT in combination with the AWG chip (Fig. 2 (a)). An image of a layered phantom consisting of three layers of scattering medium interleaved with non-scattering tape to the required depth of 1 mm has been obtained by scanning the OCT beam over the sample (fig. 2 (b)).

AWGs have also been designed and fabricated for the miniaturization of a Raman microspectrometer. On-chip portable Raman spectrometers can find many interesting applications, such as the detection of dental caries even before it is detectable with other techniques. For many applications, it is very interesting to be able to work on a confocal configuration. AWGs provide a means to deliver light at a certain depth inside the tissue surface.

One of the latest developments in the IOMS Group consists of a grated waveguide (GWG) sensing device integrated with microfluidics and micro-mechanical structures. A waveguide with a finite-length grated section acts as an optical resonator, showing sharp fringes in the transmission spectrum near the stop-band edges of the grating. Any small perturbations in the environment of the GWG, which disturb the evanescent field of the GWG resonant modes, will lead to a shift of its transmission spectrum. This effect can be exploited for many sensing applications. Recently, we have successfully fabricated silicon-nitride grated-waveguide optical cavities as compact integrated optical sensors for concentration sensing (eg., detection of DNA molecules passing on top of the device surface), label-free protein sensing (Fig. 3 (a)) and gas sensing. This last application uses a micromachined microcantilever placed on top of the sensor. As gas sticks to the surface of the microcantilever, it deforms due to stress built-up, modifying the propagation of the light in the sensor.

Finally, another very powerful bio-

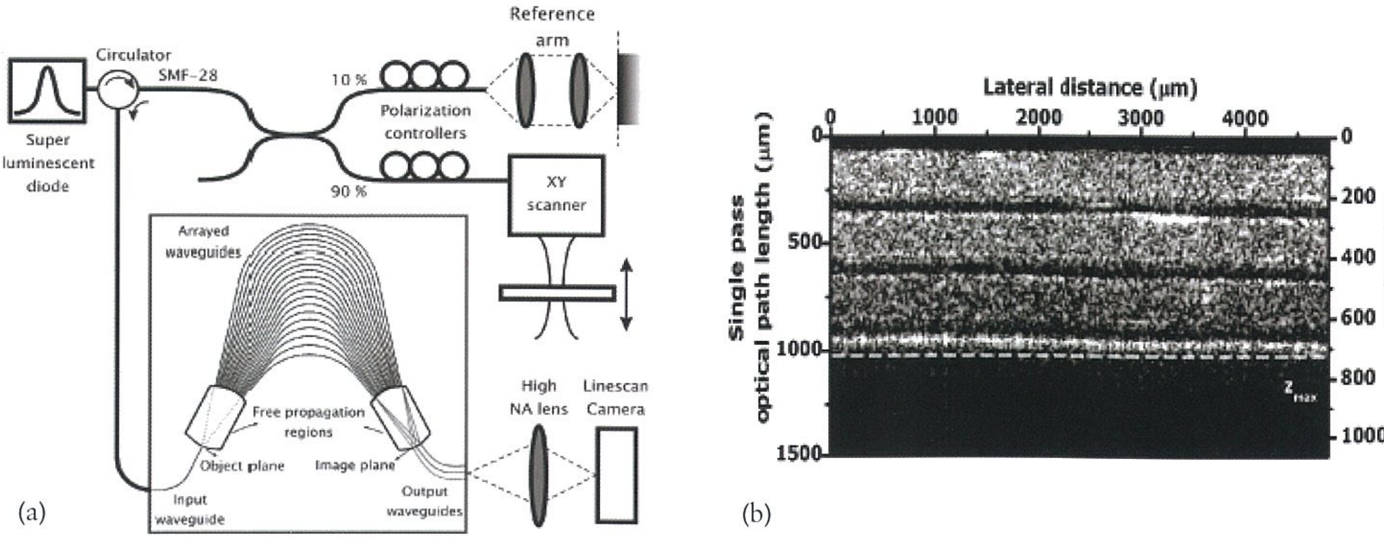
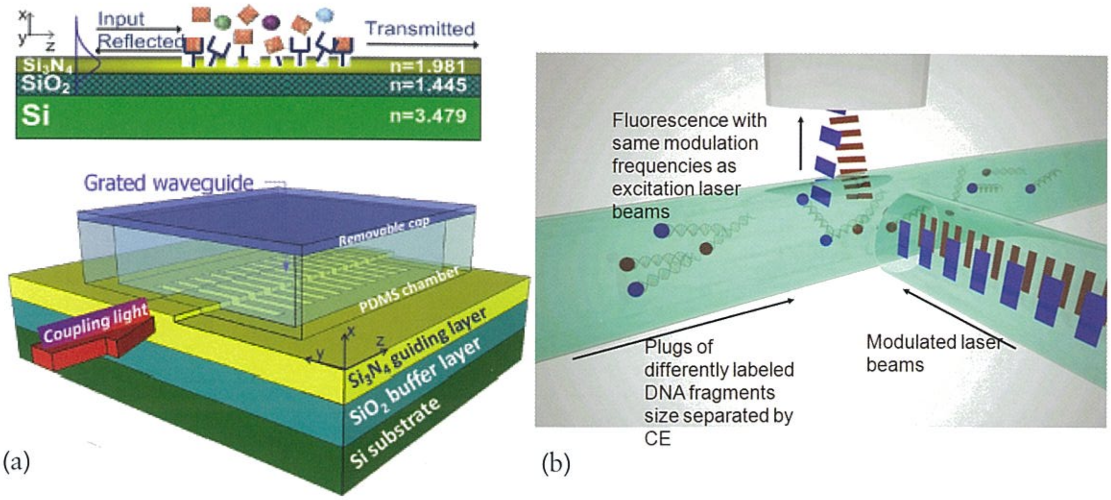


figure 2: (a) fiber-based OCT measurement set-up; (b) OCT image of the three-layered scattering phantom measured with the AWG as spectrometer in SD-OCT



(a) (b)

figure 3: (a) device for label-free protein detection. Schematic of the device showing the antigen-antibody reaction on the surface of the GWG sensor; (b) Schematic showing plugs of fluorescently labeled molecules migrating along the microfluidic channel to the detection point, where laser beams modulated with different frequencies impinge upon them. Detection is carried out with a single ultrasensitive fast detector in a 90 deg configuration

sensing technique is laser-induced fluorescence detection (LIF). In particular, sorting and sizing of DNA molecules by capillary electrophoresis, in combination with LIF, within the human genome project have enabled the genetic mapping of various illnesses. Integrated optics, together with microfabrication techniques, permits the integration of optical waveguides with microfluidic channels to produce low-cost, portable and fast on-chip bio-analysis tools, which aim at solving major challenges in medicine. Several wavelengths are typically used in order to enhance the capabilities of the technique. However, the use of several wavelengths implies the use of various sources and detectors, considerably increasing the complexity, size and cost of the instrument.

In our group we have proposed a multi-wavelength LIF detection technique that requires only the use of a single, ultra-sensitive, color-blind, fast detector. The technique is based on the modulation of each excitation wavelength at a different modulation frequency, followed by simultaneous detection of the different fluorescence signals with a single color-blind detector. Fourier transformation of the measured signal permits obtaining the fluorescence intensity of the different wavelengths (i.e., modulation frequencies) provided that the excited-state lifetime of the fluorescence dyes is significantly shorter than the applied modulation frequencies, the modulation frequencies are harmonically uncorrelated with each other and the detector can resolve the applied modulation frequencies. After applying a band-pass filter around each frequency and performing the inverse Fourier transform, the time domain data corresponding to each of the tagged DNA molecules passing in front of the detector can be obtained. Fig. 3 (b) shows a schematic representation of the detection principle.

Photonic-Electronic Convergence

In order to fully utilize the benefits of integrated photonics, it is necessary to have a means to integrate photonics and electronics in a compact and reliable way. One of the ongoing research projects at the IOMS Group deals with the convergence of photonic and electronic chips. Mirrors are being utilized to direct the output of the optical waveguides towards the corresponding photo diodes.

Conclusions and outlook

It is expected that over the coming decades photonics will impact most areas of our lives, revolutionizing societies and industries around the world. Integrated optics and nanophotonics has emerged as one of the technologies of the 21st century, hopefully permitting to overcome the challenges that limit current technologies, especially in the field of telecommunications, health and environmental monitoring. At the IOMS Group of the University of Twente we are positioning ourselves as a strong player in the field, setting the basis that will enable us to define the next generation of fully integrated nanophotonic devices. ■

References:
[1] www.utwente.nl/ewi/ioms