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Micro and Nano Lasers for Digital Photonics

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Abstract: The small size, low power and high speed of nano-lasers make them an attractive non-linear element for digital photonics. However, further miniaturization of lasers below the diffraction limit is required before digital photonics can truly compete with electronics.

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1. Introduction

The explosive growth of fiber-optic based telecommunications has focused attention again on all-optical digital processing of information encoded in an optical format. Optical signals do not suffer capacitive loading, as in electronics. So optical signal processing systems could in theory be superior to electronics in terms of bandwidth.

Furthermore, the complexity of photonic integrated circuits (PIC) is now being limited due to the lack of signal regeneration and manufacturing tolerances, similar to the situation of analog electronics in the 1960’s. There is an urgent need to move to digital processing of optical information in order to achieve VLSI complexity.

To be truly successful all-optical digital information processing systems require: a component or set of components that are Boolean complete and can be cascaded to make any digital function, the component(s) must be of microscopic size and able to be densely integrated and interconnected using integrated circuit technology (which also implies that the components have low power requirements), finally the components must operate at very high speed, to be competitive with electronics [1].

Over the past 40 years significant research has gone into trying to make components or logic gates that fulfill the above requirements. However, the lack of materials with fast, strong, low power optical non-linearities [2] has meant that high speed, complex, integrated digital optical processors have not been achieved.

Most recent work has concentrated on passive bistable systems which employ micro or nano resonators [3]. However these attempts have been remarkably unsuccessful in obtaining high speed low power devices. A number of issues have frustrated progress in this direction: 1) High power optical fields are required inside the resonator, and the field levels change dramatically for different states. Absorption leads to heating of the resonator, and slow thermal effects dominate the device response. 2) It is difficult to build high quality factor (Q) resonators and furthermore there is a tradeoff between Q and device speed, leading to fast devices requiring high optical power.

2. Lasers as logic gates

Lasers have a long history of being used to implement digital logic gates in optics [4,5]. In particular, laser gain quenching provides a suitable non-linear optical function for producing NOR and NAND gates [5]. However, these large conventional laser devices [5] consumed considerable power, had limited speed, and finally the passive waveguide technology to interconnect such active devices has only recently been widely available.

Employing micro or nano lasers for digital logic gates can address some of the disadvantages of larger conventional lasers and also passive bistable systems. Micro-ring lasers have been shown to operate at very low powers [6], this is because there is only a small amount of gain material in the cavity. Even when the laser gain material is pumped hard or far above threshold, the power level is still manageable. Furthermore as the laser size decreases, the ratio of surface area to volume increases, allowing better heat dissipation.

A high Q cavity is not required to build up a large optical field, as the gain medium compensates for losses, thus permitting high speed operation [7]. When light is injected into the laser at a resonant frequency of the laser cavity, only a small amount of input light may be needed to switch the laser light from one mode to another. Thus the amount of light in the laser cavity does not change greatly. Hence, laser based logic gates will not suffer from slow thermal effects caused by the input signals, as occurs in passive systems.

Finally, the recovery time of the laser can in theory be arbitrarily fast, by simply pumping the laser further above threshold [7] (For optical signal modulation, where non-linear gain suppression effects do not limit modulation bandwidth, as is the case in electrical modulation.)
Unfortunately micro and nano lasers tolerate only limited coupling to the external environment. So in-order to switch the lasers on and off efficiently, light needs to be injected at a wavelength which is resonant in the laser cavity, i.e. injection locking. We have shown that via injection locking micro-lasers are able to switch each other, and can form simple digital systems [8].

3. Further miniaturization of lasers

Higher modulation speed for less power is possible in lasers by decreasing the laser cavity modal and active material volumes. With dielectric cavities there is a fundamental limit to how small the cavity modal volume can be [9]. Furthermore, even in the dielectric cavities with the smallest modal volumes, a much larger structure is required to confine the light to the central region of the device. However, in metallic structures light can be confined and guided to below the diffraction limit. Of particular interest are the surface plasmon polariton gap waveguides (SPGW) [10,11]. Such structures have been shown in theory to confine light in two dimensions to below the diffraction limit.

A method to construct such a waveguide would be to employ a semiconductor heterostructure as shown in Fig 1. Here lithography, dry etching, and selective chemical etching can be used to create a three dimensional form. A thin layer of insulator can be deposited on the form. Finally metal such as gold or silver can be deposited over the form to create a SPGW. The optical mode of the waveguide is strongly confined to the InGaAs region [10,11]. The InGaAs region may be shrunk in the x and y dimensions to several tens of nanometers, while still effectively guiding wavelengths in the 1550nm range.

![Fig. 1: A) Structure of an active surface plasmon polariton gap waveguide. Lithography, dry etching and selective wet etching can be used to form the three dimensional nano structure. Metal can be deposited by evaporation around the form to complete the waveguide and provide a top electrical contact. B,C) Results of FDTD simulation of section of SPGW one half wavelength long, and terminated by metal ends. The size of the InGaAs region is 26x26x82nm. Shows the electric field intensity of the resonant mode. B: E^2 through the x-y plane. C: E^2 through the y-z plane](image)

Such a structure can also serve as an active waveguide offering gain to signals passing along it. This is possible because the central InGaAs region can be electrically pumped with carriers. The top of the InP pillar which is in contact with the metal cladding can form one electrical contact. The other electrical contact is connected to the InGaAs region via the InP substrate.

Resonant cavities suitable for lasers could be constructed from these waveguides by employing Bragg grating reflectors [12]. Or by simply having a section of waveguide an integer number of half wavelengths long, encapsulated in metal. Finite difference time domain (FDTD) simulations of such a cavity are shown in Fig. 1. Here the InGaAs region is 26nm x 26nm x 82nm in size. For simplicity, the insulating layer is not present. The surrounding metal is silver.

The simulation results show the resonant mode of the cavity is tightly confined to the InGaAs region, Fig 1. From the simulation the resonant wavelength of the cavity is found to be 1380nm, the quality factor (Q) is 53, and the overlap of the optical mode with the active region, the confinement factor $\Gamma$ is 0.43. The material gain $g$ required to overcome losses in the cavity can be found from these cavity parameters: $g=2\pi/(\lambda\Gamma Q)$, to be approximately 2000 cm$^{-1}$. Such gain can in theory be achieved with bulk InGaAs lattice matched to InP. Quantum confinement may also increase the material gain [13] in such small structures, making it easier to achieve lasing threshold.
The volume of active material is so small in such a laser structure, that it is possible to achieve intrinsic modulation bandwidths in the terahertz region, with only a few tens of microamps of current. Furthermore with such a small device encapsulated in metal, the problems of device self heating can be minimized.

Fig. 2 shows scanning electron microscope pictures of sections of SPGW that we have made. Here the InGaAs layer is 300nm thick, requiring a bulge instead of an indentation to increase optical confinement. The insulating layer is 25nm thick SiN. The InGaAs material was electrically pumped via the top electrical contact, and a large area lateral contact. Such structures demonstrate that active SPGWs as shown in Fig. 1 are feasible.

4. Conclusions

The rapid progress in integrated optics and laser technology in recent years means that micro and nanolasers are a potential solution for digital photonics. In theory it is possible to satisfy all the requirements for a digital system using micro and nano-lasers and passive integrated optics components. Thus providing medium scale integration digital systems with moderate performance. However to truly exploit the high bandwidth potential of optics, and also achieve high integration levels will require further progress in the miniaturization of lasers. Further miniaturization can in theory be achieved via metallic nano structures.

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6. References