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Citation for published version (APA):
Hill, M. T. (2007). Micro and nanolasers for digital photonics. In *Proceedings of the 13th European conference on integrated optics (ECIO 2007), 25-27 April 2007, Copenhagen, Denmark* (pp. WC0-64/67)

Document status and date:
Published: 01/01/2007

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Micro and Nanolasers for digital photonics

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Abstract: *There is an increasing need for high speed digital like processing of signals in integrated optics. The use of current micro and nano lasers to address this issue is examined. Further developments in nano laser technology will improve the case for their use in digital systems. Some of the directions of these further developments in nano lasers are also examined.*

Introduction

The explosive growth of fibre-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.

A good review of the requirements for a digital logic device to be used as a building block for larger systems is given in [1]. Some important requirements relevant to optical systems are that device inputs are isolated from the device outputs and visa versa. Furthermore there should be no reflection of energy form the gate output back into the gate. Or if there is reflection then it shouldn’t affect the gate operation.

Over the past 40 years significant research has gone into trying to make components that fulfil 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 [3-6]. However these attempts have been remarkably unsuccessful in obtaining high speed low power digital elements. 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 resonantor, and slow thermal effects dominate the device response.

2) It is difficult to build high quality factor (Q) resonators and furthermore there is a trade-off between Q and device speed, leading to fast devices requiring high optical power.

Lasers as digital elements

Lasers have a non-linear optical characteristic suitable for digital operations, and also they are a light source for the optical signals. So it is not suprising that the proposal of using lasers as a digital element has a long history [7-8]. However, these large conventional laser devices 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 elements 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 [9], [10], 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 [11]. 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 [11] (For optical signal modulation, where non-linear gain suppression effects do not limit modulation bandwidth, as is the case in electrical modulation [12].)

Unfortunately micro and nano lasers tolerate only limited coupling to the external environment. So inorder 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 [13]. We have shown that via injection locking microlasers are able to switch each other, and can form a simple digital systems [14].

However more is required than the system presented in [14] for a digital building block (such as a 2 input NOR gate), that can be used to make arbitrarily large and complex digital systems. In particular the basic requirements of isolating inputs from outputs in the device and avoiding reflections need to be satisfied. To achieve input/output isolation requires at least three orthogonal cavity modes in the micro/nano laser, two for the inputs and one for the output. Furthermore some filtering is required on the device output to block inputs propagating to the outputs and visa versa. Systems using differences in wavelength to obtain orthogonality have been been demonstrated in integrated systems [15], albeit with large lasers.

Ring lasers coupled with a passive ring resonator can have orthogonal modes and provide isolation between inputs and outputs by using modes one free spectral range of the resonator away from each other. The operation of such a gate which can be implemented in active/passive photonic integrated circuit technology is examined in [16]. Additionally the problem of reflections is solved, as in theory no reflections occur in such ring systems.

Single defect photonic crystal lasers [17] offer the possibility of even smaller laser devices, with possibly lower power consumption. Furthermore very high speed operation has been demonstrated in these devices [11]. Photonic crystal cavities also posses a large variety of resonant modes. In such cavities spatial orthogonality can be used to separate the input and output modes.

Consider a modified single defect cavity in a triangular air hole photonic crystal [17] fig. 1. Here just the hexapole mode and doubly degenerate quadrapole modes are considered, a total of three modes. These three modes have a high Q and the resonant frequencies can overlap and be tuned independently by modifying the surrounding air-holes. Remarkably, there exists waveguides with a particular direction and end point, which will couple strongly to one cavity mode and only weakly to the other modes. By choosing an output waveguide which only couples to the main lasing mode and not the two input modes, optical isolation of the output from the inputs is achieved. Furthermore, the inputs can be isolated from the output by choosing input waveguides which only couple to the input modes. Fig. 2 shows this selective excitation for two of the modes.

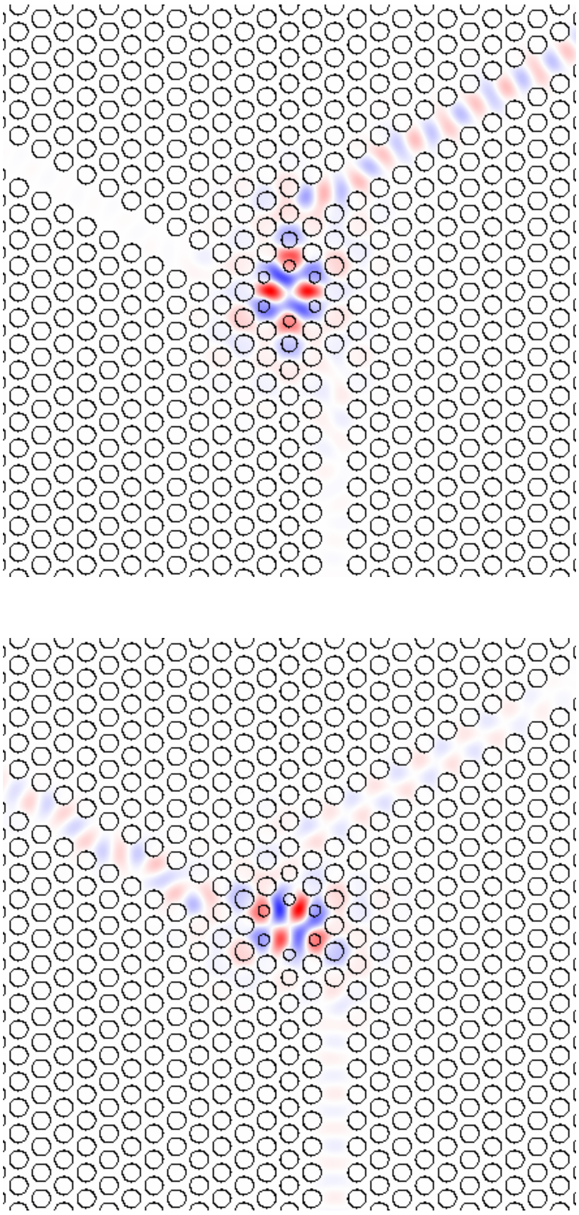

Fig. 1: Finite difference time domain simulation showing selective coupling of cavity modes to just one particular waveguide. The vertical H field is shown in color. Top: even quadrapole mode of single defect cavity. Bottom: odd quadrapole mode.

However, reflections of the output signal back into the driving laser is a difficult problem to solve with single defect cavities, although some solutions exist. This lack of reflections is one area where ring lasers excel, as in theory there is no reflection of light injected into a ring laser.

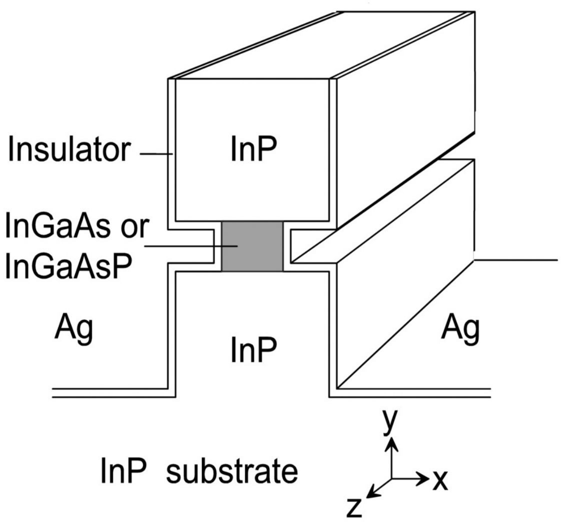

Fig. 2: Structure of an active surface plasmon polariton gap waveguide. Lithography, dry etching and selective wet etching can be used to form the three dimensional nano structure. Metal can be deposited by evaporation around the form to complete the waveguide and provide a top electrical contact.

Further miniturization of lasers

With dielectric cavities there is a fundamental limit to how small the cavity modal volume can be [18]. 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) [19-20]. 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 2. Here lithography, dry etching, and selective chemical etching [21] 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 [19-20]. 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.

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 is 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 [22]. 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. 3. Here the InGaAs region is 26nm x 26nm x 82nm in size. For simplicity, the insulating layer wasn't present. The surrounding metal was silver.

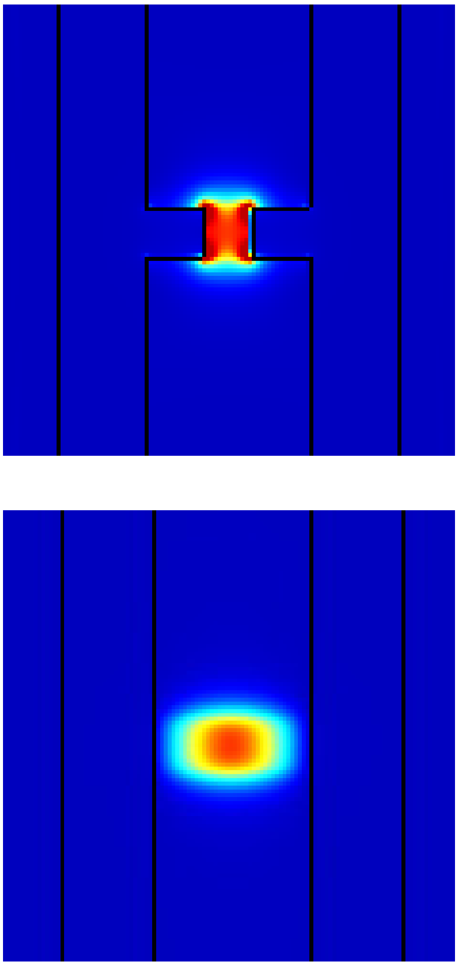

Fig. 3: Results of FDTD simulation of section of SPGW one half wavelength long, and terminated by metal ends. The size of the InGaAs region is 26x26x82nm. Shows the electric field intensity of the resonant mode. Top: E^2 through the x-y plane. Bottom: E^2 through the y-z plane

The simulation results show the resonant mode of the cavity is tightly confined to the InGaAs region, Fig 3. 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 Γ [23] 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 be in theory be achieved with bulk InGaAs lattice matched to InP. Quantum confinement may also increase the material gain [24] 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.

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 nanolasers 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 miniturization of lasers. A method that this can in theory be achieved is via metallic nano structures.

Acknowledgments

This work was supported by the Netherlands Organization for Scientific Research (NWO) through the "NRC photonics" grant.

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