Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Science Letters:

The Moore's Law for photonic integrated circuits

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Received Oct. 10, 2006; revision accepted Oct. 15, 2006

Abstract: We formulate a "Moore's law" for photonic integrated circuits (PICs) and their spatial integration density using two methods. One is decomposing the integrated photonics devices of diverse types into equivalent basic elements, which makes a comparison with the generic elements of electronic integrated circuits more meaningful. The other is making a complex component equivalent to a series of basic elements of the same functionality, which is used to calculate the integration density for functional components realized with different structures. The results serve as a benchmark of the evolution of PICs and we can conclude that the density of integration measured in this way roughly increases by a factor of 2 per year. The prospects for a continued increase of spatial integration density are discussed.

Key words: Moore's Law, Photonic integrated circuit (PIC), Photonic lightwave circuit (PLC), Photonic integration density, Photonic filters, Photonic multiplexing

doi:10.1631/jzus.2006.A1961 **Document code:** A **CLC number:** TN2

INTRODUCTION

Photonic circuits are currently many orders of magnitude larger in physical dimensions than their electronic counterparts. Whereas FET type transistors have lengths on the order of 50 nm, passive optical devices, even those based on photonic crystals, have sizes on the order the wavelength, 1 μm for customary telecom applications. For active devices the sizes are even larger, at least in length, essentially depending on the matrix element of the interaction in question. Regarding the packing density determining transversal integration, the field extensions are on the order of the wavelength, when dielectrics are used, in contrast to electronics, where the metallic conductors give much better confinement. In addition, electronics features discrete devices with dimensions much smaller than the wavelengths involved, something so far missing in photonics.

In this paper, we formulate a photonics version of famed Moore's Law (Moore, 1965), a law that has turned out to be a formidable prediction of the future, or maybe has formed the future. We point out the differences that have to be taken into account. As an example we can take an 8×8 arrayed waveguide grating (AWG), which in view of its functionality cannot reasonably be regarded as one single element. Difficulties of this nature do not appear in integrated electronics. Some comments on ultimate limits of photonics integration are therefore given.

MOORE'S LAW FOR PHOTONICS, FORMULATED IN TERMS OF INTEGRATION DENSITY

Moore's Law concerns electronic integration density and its evolution (exponential progress) in time. The ultimate limit here is power dissipation, because using irreversible entropy lowering devices such as NAND gates will, according to basic thermodynamics, always come with heat generation. Only a certain amount of this heat can practically be removed from the chip. Here the exponential progress in the electronic integration density can be attributed to advances in lithography, design and technology in general.

Before achieving a Moore's Law for photonic integrated circuits (PICs), some remarks on basic differences are in place:

(1) The Moore's Law for electronic ICs pertains to circuits with generic elements (transistors, resistors, capacitors), some fraction of them are active in the sense that they dissipate power, as noted above. These elements are fabricated by standard processes, applicable to all elements, in one material, silicon, with its natural passivating oxide.

(2) The Moore's Law for photonics will have to take into account the fact that no generic elements like in electronics exist. On the contrary, the elements are different and employ widely different fabrication processes, and the materials are different too (III-V semiconductors, silicon, ferroelectrics, polymers, etc).

(3) There is no or small power dissipation in a passive case (such as AWGs, switch arrays in ferroelectrics …) but "high" power dissipation for active devices (lasers, optical amplifiers …).

We take two approaches to deal with the problem as follows.

Method one

The first method is to transform more complex PICs to "equivalent elements", as described below, for a reasonably meaningful comparison. Although this is not an exact analogy to electronics, and in a sense it mixes up true integration density in terms of e.g. waveguides per mm, and functionality; and in addition it does not weigh in performance. We feel that it is, in view of the above issues, a reasonable approach. The alternative would be to treat for example an entire 64×64 AWG as one element. Clearly it is not adequate too. Thus, for PLCs, we define the generic elements as:

For passive and non-power-dissipating devices:

(1) 1×2 couplers;

(2) Directional couplers, crossing waveguide couplers;

(3) Filters, including resonators (Bragg filters, photonic crystals …);

(4) Modulators (electrooptic, reverse biased semiconductor modulators).

Here, in the case of modulators, the power is dissipated in the driving circuitry.

For active devices:

(1) Lasers;

(2) Amplifiers;

(3) Forward biased semiconductor devices;

(4) Detectors (border case).

As an example, a Mach-Zehnder interferometer is equal to two elements (couplers). A quarter wave shifted DFB laser would be two elements. We proceed to an $N_1 \times N_2$ AWG (Fig.1a), with N connecting waveguides and calculate the equivalent number of elements N_{eq}. We construct the equivalent number of 1×2 couplers (Fig.1b), and arrive at the total number of $N_{eq}=N_1(N-1)+N_2(N-1)$. The formula used for this is:

$$N_1 \cdot \sum_{\nu=0}^{ld(N)-1} 2^{\nu} + N_2 \cdot \sum_{\nu=0}^{ld(N)-1} 2^{\nu}.$$

In the same way we can treat other devices. This is admittedly a rough and somewhat arbitrary method, since it does not consider any difference in e.g. processing for a laser and a dielectric 1×2 coupler. However, it will still give an idea of complexity.

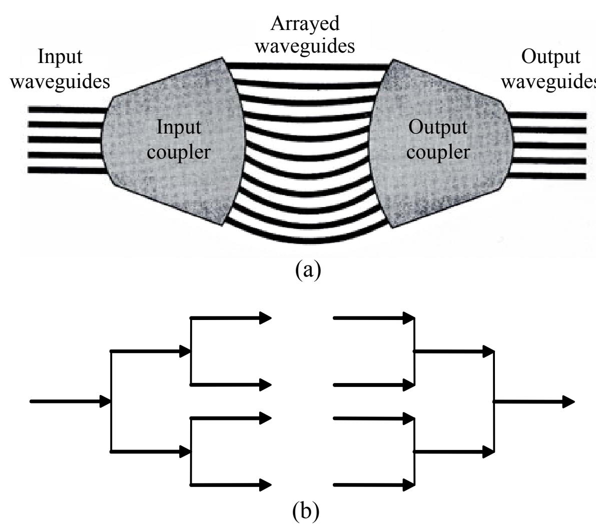

Fig.1 (a) Arrayed waveguide grating (AWG) schematic, showing input and output waveguides as well as the multimode interference couplers and the waveguide array connecting them. The equivalent number of 1×2 couplers is $N_{eq}=2N_1(N-1)$, if we have an $N_1 \times N_1$ device and N connecting waveguides. (b) Representation of a 4×4 AWG with 1×2 couplers, showing only one input/output

Method two

The first method can be used to treat components such as star couplers and arrayed waveguide gratings. However, it may not be optimal in calculating the integration density for functional components realized with different structures. For example, we consider an $N_1 \times N_2$ (de)multiplexer, which can be realized by either an $N_1 \times N_2$ array of micro-ring resonators (MRRs) or an $N_1 \times N_2$ AWG. According to the first method, an $N_1 \times N_2$ array of MRRs give $N_{eq(MRR)}=3N_1 \times N_2$ elements since each MRR is equivalent to 3 elements (i.e., two couplers and one ring). With Method One, an $N_1 \times N_2$ AWG demultiplexer gives $N_{eq}=N_1(N-1)+N_2(N-1)$, which is much larger than the equivalent number $N_{eq(MRR)}$ for an array of MRRs since N is usually much larger than $N_{1,2}$. In this way, an $N_1 \times N_2$ AWG has likely much higher integration density as compared with an $N_1 \times N_2$ array of MRRs if the occupied area is identical. However, an $N_1 \times N_2$ AWG and an $N_1 \times N_2$ array of MRRs function are the same actually. It is more reasonable to make them equivalent to the same number of basic elements. Therefore, we propose the second method as a complementary algorithm for the calculation of the integration density.

In Method Two, we make a complex component equivalent to a series of basic functional elements. Every type of functional component has a corresponding basic functional element. In this way, two components with the same functionality would have the same equivalent total numbers of basic elements. Then the integration density is determined by their occupied area. For example, for (de)multiplexer, the basic element is a pass-band filter for one wavelength, e.g., a four-port MRR. Thus, an $N_1 \times N_2$ AWG is equivalent to an $N_1 \times N_2$ array of basic filters.

The main difference between the two methods is choosing different basic elements. For Method One, a 1×2 splitters etc. are the basic elements. For Method Two, different basic functional elements are used for different kinds of functional components. We calculated the integration density of some typical PIC devices published from 1985 to present by using these two methods (Granestrand *et al*., 1986; Wisely, 1991; Gustavsson *et al*., 1992; Trinh *et al*., 1997; Menezo *et al*., 1999; Bissessur *et al*., 1995; 1996; Sasaki *et al*., 2005; Dai *et al*., 2006; Smit, 2005; Inoue *et al*., 1988; 1995; Takahashi *et al*., 1990; 1994; 1995; Soole *et al*., 1991; 1995; Zirngibl *et al*., 1992; 1993; Okamoto *et al*., 1995; 1996; Kohtoku *et al*., 1997; Ishii *et al*., 1998; 2001; Hida *et al*., 2000; 2001; Dumon *et al*., 2004; Bozhevolnyi *et al*., 2006; Takato *et al*., 1990; Adar *et al*., 1993; Sun *et al*., 1997; 1998; Hibino, 2002; de Peralta *et al*., 2003; Janz *et al*., 2004; Kamei *et al*., 2005; Maru *et al*., 2005; Cremer *et al*., 1992; Bach *et al*., 1996; den Besten *et al*., 2002; Barbarin *et al*., 2004; Luff *et al*., 2003; Dumon *et al*., 2004; Vellekoop and Smit, 1991; Tachikawa *et al*., 2006).

RESULTS AND DISCUSSIONS

In Fig.2 we show the evolution in integration density for photonics (rather than total number of elements). We have taken references (Granestrand *et al*., 1986; Wisely, 1991; Gustavsson *et al*., 1992; Trinh *et al*., 1997; Menezo *et al*., 1999; Bissessur *et al*., 1996; Sasaki *et al*., 2005; Dai *et al*., 2006) as examples, and selected the best results according to our Method One, which in a sense overemphasizes the data for AWGs. It can be seen that the increase in density actually outpaces the Moore's Law prediction, since we have very roughly a factor of 2 per year. Thus, integration density has increased dramatically, but in total number of elements, not much progress is shown over and above (Granestrand *et al*., 1986), results in nearly 20-years old vintage.

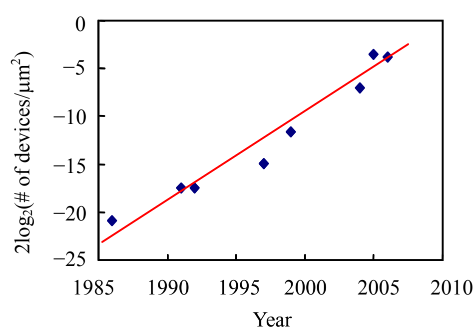

Fig.2 The Moore's Law in PLC obtained by Method One (Granestrand *et al*., 1986; Wisely, 1991; Gustavsson *et al*., 1992; Trinh *et al*., 1997; Menezo *et al*., 1999; Bissessur *et al*., 1996; Sasaki *et al*., 2005; Dai *et al*., 2006)

The numbers given in Fig.2 are several orders of magnitude larger than the ones presented in (Smit, 2005), as different methods were used to calculate integration. Also, the rate of increase of integration is lower in (Smit, 2005) than in the present analysis.

We also summarized the development of the integration density of PLCs by using Method Two considering the integrated filters such as Mech-Zehnder Interferometers, AWGs, and etched diffraction gratings. Fig.3 shows the calculated integration density from 1988 to present (see the discrete dots) and the corresponding linearly fitted line. In Fig.3 the data for the integrated filters based on different materials (such as SiO_2, InP, and Si) are included. From this figure one would see that the integration density almost tripled every year.

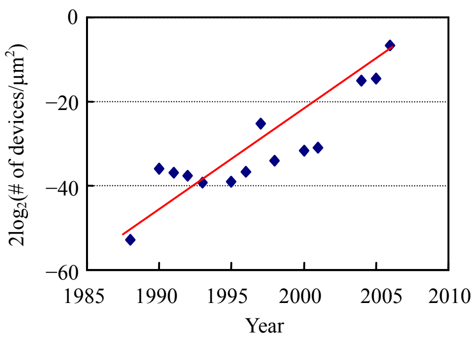

Fig.3 The Moore's Law in the development of the integration density of optical filters (Sasaki *et al.*, 2005; Inoue *et al.*, 1988; Takahashi *et al.*, 1990; Soole *et al.*, 1991; Zirngibl *et al.*, 1992; 1993; Okamoto *et al.*, 1995; 1996; Mohtoku *et al.*, 1997; Ishii *et al.*, 1998; Hida *et al.*, 2000; 2001; Dumon *et al.*, 2004; Bozhevolnyi *et al.*, 2006)

In order to observe the influence of the material on the integration density, Fig.4 shows the development in the integration density for the PLC based on InP, SiO_2, and Si, respectively. From the fitted lines in Fig.4a, one can see the integration density of integrated filters based on SiO_2 improves with a factor of 2.5 per year. However, the integration density reached the maximum in 2002. It is difficult to have a higher integration density with SiO_2 for being limited by small refractive index of the SiO_2 buried waveguides.

By using InP waveguides with a strong confinement at the lateral direction, one can have a higher integration density (Fig.4b). Figs.4a and 4b show also that InP can provide higher integration density than SiO_2 does because of a smaller bending radius.

Fig.4c shows the integration density of Si-based integrated filters from 1997 to present. Since the refractive index contrast between Si and SiO_2 (or air) is very large, it is possible to realize some ultracompact

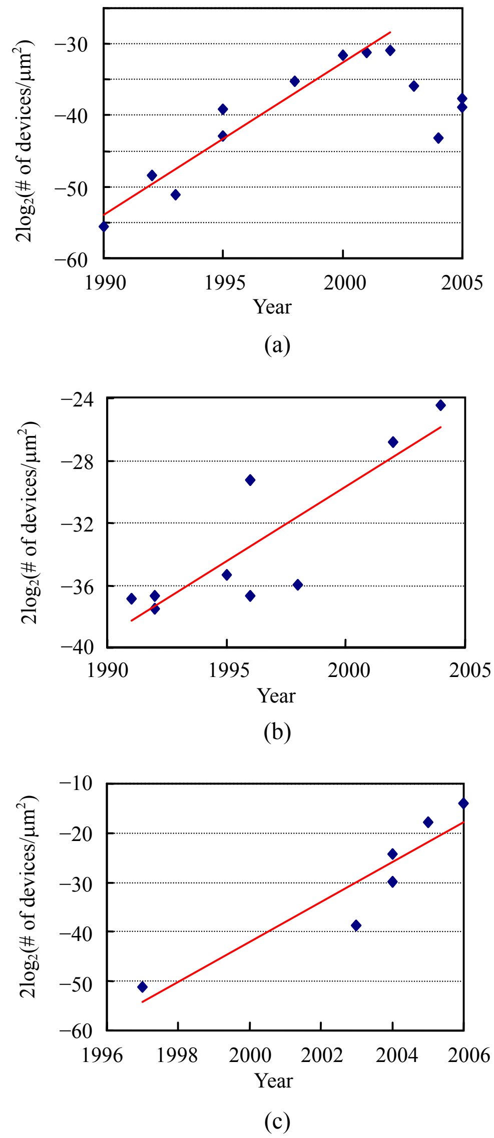

Fig.4 Moore's Law for the integration density of optical filters based on (a) SiO_2 (Okamoto *et al.*, 1995; Hida *et al.*, 2000; 2001; Takato *et al.*, 1990; Adar *et al.*, 1993; Inoue *et al.*, 1995; Sun *et al.*, 1998; Hibino, 2002; de Paralta *et al.*, 2003; Janz *et al.*, 2004; Kamei *et al.*, 2005; Maru *et al.*, 2005); (b) InP (Bissessur *et al.*, 1996; Soole *et al.*, 1991; 1995; Zirngibl *et al.*, 1992; Ishii *et al.*, 1998; Cremer *et al.*, 1992; Bach *et al.*, 1996; den Besten *et al.*, 2002; Barbarin *et al.*, 2004); (c) Si (Trinh *et al.*, 1997; Sasaki *et al.*, 2005; Dai *et al.*, 2006; Janz *et al.*, 2004; Luff *et al.*, 2003; Dumon *et al.*, 2004)

PLCs including filters. The integration density of Si-based integrated filters has a very rapid improvement with a factor of 5.5 per year in the past several years (Fig.4c). This is due to the use of Si nanowire waveguides.

An AWG (de)multiplexer is a typical integrated filter. The Moore's Law for the development in the integration density of AWG (de)multiplexers based on different materials (for each year we pick up the best result) (Fig.5) shows an improvement with a factor of 2 per year.

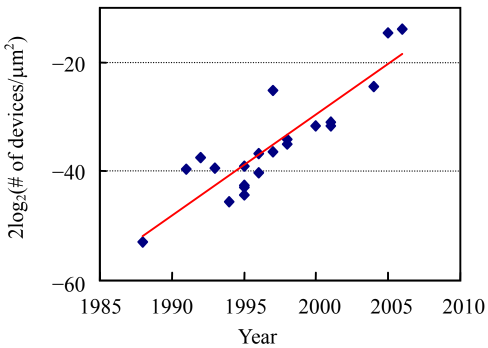

Fig.5 The Moore's Law for AWG (de)multiplexers (regardless of the material used) (Sasaki *et al*., 2005; Dai *et al*., 2006; Smit, 2005; Inoue *et al*., 1988; Zirngibl *et al*., 1992; 1993; Okamoto *et al*., 1995; 1996; Kohtoku *et al*., 1997; Ishii *et al*., 1998; 2001; Hida *et al*., 2000; 2001; Sun *et al*., 1997; 1998; Barbarin *et al*., 2004; Vellekoop and Smit, 1991; Takahashi *et al*., 1994; 1995; Bissessur *et al*., 1995; Tachikawa *et al*., 1996)

In general, the factors that have brought about rather dramatic increase in integration density in photonics are design, lithography and novel materials (going from ferroelectrics via silica to silicon).

PROSPECTS FOR INCREASED INTEGRATION

Structures with feature sizes in sub-wavelength scale, for instance tens of nm for a 1000 nm vacuum wavelength would certainly increase the integration density. Such structures cannot be based on high index contrast dielectric waveguides, such as Si nanowires. The possible alternative is with negative ε materials, such as metals. The simple type of electromagnetic dispersion that found in metal/dielectric waveguide structure provides some challenging prospects for nanophotonics such as waveguide propagation wavelengths in the X-ray region of light in visible wavelengths. This is made possible by huge reduction in group velocity that can be achieved. This behavior is, however, in today's materials accompanied by (very) high optical losses, but still offers very intriguing avenues towards real integration and nanophotonics.

Here, one could either rely on "TM_{-1}" or plasmon mode that attached to a metal-dielectric interface, or enclose the optical field arbitrarily well within two metal walls, at the expense of large losses (Bozhevolnyi *et al*., 2006).

Regarding the power dissipation, which is the limiting factor today in electronics, we make the comment that this will probably severely limit integration density, due to the thermal sensitivity of the devices involved.

CONCLUSION

In this paper, we have summarized in the development of the integration density of PICs. By using two different approaches, we assessed the "Moore's Law" for PICs. One is based on breaking down integrated photonics devices in diverse types into equivalent basic elements. The other is to make a complex component equivalent to a series of basic elements of the same functionality. The improvement of the integration density of PICs depends on the materials used, on improved lithography as well as advances in modeling during the 20-year period studied. At present, it seems that Si nanowire waveguides can give passive PICs the highest integration density. It appears that novel materials will be demanded to ensure a sustainable development in integration density. Metal-like materials, though with lower optical losses than metals at room temperature, could play such a role.

ACKNOWLEDGEMENT

We thank Jun Song and Yaocheng Shi for gathering some parts of the data from the literature.

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