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# Nanophotonics and negative $\varepsilon$ materials*

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**Abstract:** The feasibility of using metal optics or negative $\varepsilon$ materials, with the aim of reducing the transversal extent of waveguided photonic fields to values much less than the vacuum wavelength, in order to achieve significantly higher densities of integration in integrated photonics circuits that is possible today is discussed. Relevant figures of merit are formulated to this end and used to achieve good performance of devices with today's materials and to define required improvements in materials characteristics in terms of decreased scattering rates in the Drude model. The general conclusion is that some metal based circuits are feasible with today's matals. Frequency selective metal devices will have $Q$ values on the order of only 10~100, and significant improvements of scattering rates or lowering of the imaginary part of $\varepsilon$ have to be achieved to implement narrowband devices. A photonic "Moore's law" of integration densities is proposed and exemplified.

**Key words:** Integrated optics circuit, Optical surface wave, Optical waveguide, Microwave circuit, Waveguide
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## INTRODUCTION

Photonics circuits or integrated optics circuits are currently 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 photonics crystals have sizes on the order of wavelength of 1 μm. For active devices the sizes are even larger, essentially depending on the matrix element of the interaction of interest. 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 metallic conductors allow much better confinement. In addition, electronics features discrete devices with dimensions much smaller than the wavelengths involved, something so far not possible in photonics.

Thus, the concept of nanophotonics seems so far elusive, since nanotechnology is generally defined as a technology involving feature sizes in nanometer range (and their ensuing physical effects) whereas conventional photonics devices and technology exhibit characteristic sizes on the order of the wavelength squared, 1 μm$^2$, in cross section (transversely) and 100~10000 μm in length. Structures with lateral feature sizes on the sub-wavelength scale—say 10 nm for a 1000 nm vacuum wavelength—are certainly challenging aspects of real nanophotonics. Such structures cannot be based on high index contrast dielectric waveguides, e.g., Si nanowires, as mentioned above, but another possibility is given by negative $\varepsilon$ materials, such as metals. Here, one could either rely on the "TM$_{-1}$" or plasmon mode or optical surface wave mode, of a metal-dielectric interface, or enclose the optical field arbitrarily well within two metal walls, at the expense of large losses (Barnes *et*

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*al*., 2003). These attempts to confine fields to extremely small volumes address the important issue of photonic integration.

Also, the simple type of electromagnetic dispersion, found in a metal/dielectric waveguide structure, offers some challenging prospects of nanophotonics such as waveguide propagation wavelengths in the X-ray region for light of visible wavelengths. This is made possible by the huge reduction in group velocity that can be achieved. This behaviour is, however, in today's materials accompanied by (very) high optical losses, but still offers very intriguing avenues towards real integration and nanophotonics. Thus, it is worthwhile to compare different optical waveguide structures, such as coaxial cables and other structures, based on microwave engineering, using certain defined figures of merit. While these figures of merit are important for assessing the relative competitiveness of various structures, given today's materials, it is also important to quantify how much today's materials have to be improved, primarily regarding optical losses, for various applications to be viable.

## NANOPHOTONICS AND NEGATIVE $\varepsilon$ MATERIALS

We now turn to the issue of figures of merit for the waveguides in order to try to quantify the usefulness of metal-waveguides for different applications. We use the so called Drude model (Born and Wolf, 1980) to describe the optical properties of the metal.

Waveguides are fully described by their field components as a function of spatial coordinates and frequency. For comparison of different waveguides in our context, this information is too detailed. For our purposes it is sufficient to characterize the waveguide with the propagation constant $\alpha_z$+j$\beta_z$, the transverse fields confinement, and in some cases the characteristic impedance. Some figures of merit are defined below based on the measures above, describing the integration feasibility.

(1) The transverse field confinement can be expressed in several ways (e.g., the width can be described with a 3 dB intensity width or a normalized central second order moment of intensity distribution). For a planar metal/dielectric waveguide with a one dimensional (1D) cross section with exponentialy decaying field, we use in this paper a confinement measure $C_\mathrm{T}$ (which should be large) defined as the inverse of the summed penetration depths, i.e., $C_\mathrm{T}=(\alpha_{x2}^{-1}+\alpha_{x1}^{-1})^{-1}$. Two-dimensional (2D) cross sections need a 2D confinement measure. The confinement measure should be large as this allows placing waveguides near each other while still avoiding crosstalk.

(2) The unloaded $Q$ value of a waveguide describes the potential to make filters with small relative bandwidth, which is $1/Q$. The $Q$-value is defined as $Q=\omega_0/\Delta\omega$, where $\omega_0$ is the center angular frequency and $\Delta\omega$ is the angular frequency bandwidth. $Q$ is given by, including dispersion (Grivet, 1976):

$$Q=\omega\frac{\partial\beta_z/\partial\omega}{2\alpha_z}=\frac{v_\mathrm{phase}}{v_\mathrm{group}}\frac{\beta_z}{2\alpha_z} =-\frac{n_\mathrm{group}}{2n_z''}=-\frac{n_z'+\omega(\partial n_z'/\partial\omega)}{2n_z''}, \quad (1)$$

where $\beta_z$ is the phase constant in propagation direction $z$, $\alpha_z$ is the attenuation constant, $v_\mathrm{phase}$ is the phase velocity, $v_\mathrm{group}$ is the group velocity, $n_\mathrm{group}$ is the group index and $n_z=n_z'+\mathrm{j}n_z''$ is the mode index. This $Q$-value gives the $Q$ of a resonator based on waveguide with 100% reflecting mirrors, hence, any real resonator, with coupling to the outside world, has a lower $Q$-value, the so called loaded $Q$-value.

(3) The product of $Q$-value and transverse confinement $C_\mathrm{T}$, i.e., $QC_\mathrm{T}$, is in some cases found to be a function of only the metal properties. This means that there is a direct trade off between them. This does not pertain to cases such as a metal/dielectric interface, when the sum of the real parts of the dielectric constants is close to zero.

(4) In order to make very short resonators, one defines a figure of merit as the product of the $Q$-value and the longitudinal confinement, i.e., $QC_\mathrm{L}$. For the half wavelength resonator this is in many cases the same as $Q\beta_z$.

All these figures of merit have been calculated for the cases of metal/dielectric and metal/dielectric/metal (Berglind and Thylén, submitted), using the model in (Born and Wolf, 1980). As an example we calculate what is needed for a dense wavelength division multiplexing (WDM) system filter, which, to comply with the ITU grid, should give a bandwidth

$\Delta f$<100 GHz. We use Fig.1 configuration and assume a metal separation=vacuum wavelength/100 =15 nm. The attenuation can be calculated to be 2.8 dB/μm and using Eq.(1) we can calculate $Q=\omega_0/\Delta\omega=23$ with reasonable assumptions, where $\omega_0$ is the center angular frequency and $\Delta\omega$ is the angular frequency bandwidth.

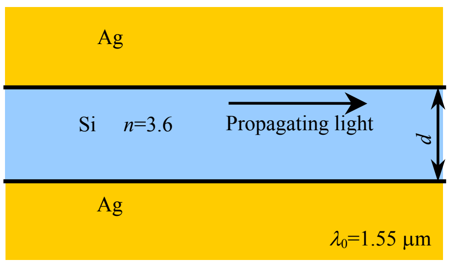


**Fig.1 Metal/dielectric/metal waveguide, used as a resonator together with mirrors at both ends. Due to the high losses of the metal, loaded *Q* values in the range of 10~100 are obatined, this is not enough for many applications, and better materials by a factor of 100~1000 are required**

However, even when using $\Delta f$=100 GHz, we get a required $Q$ value of approximately 200 THz/100 GHz=2000. The conclusion is that the scattering rates in metals or equivalent properties in other materials have to be improved by more than a factor of 100 in order to make a suitable grid filter.

## A MOORE'S LAW FOR PHOTONICS

As a benchmark on today's integration, and to put the metal optics above into perspective, we attempt to formulate a "Moore's law" for photonic circuits and compare it to Moore's law in electronics. There are a number of boundary conditions for this:

(1) Moore's law for electronic ICs pertains to circuits with generic elements (transistors, resistors, capacitors), some fraction of which are active.

(2) "Moore's law" for photonics (photonics lightwave circuits, PLCs) will have to take into account that no generic elements like those in electronics exist, so we have to transform more complex PLCs to "equivalent elements" (see below).

(3) There is no or small power dissipation in the passive case (such as the arrayed waveguide gratings, AWGs, switch arrays in ferroelectrics, etc.) and there is "high" power dissipation for active devices (lasers, optical amplifiers, etc.).

For the photonic PLCs, the generic elements we propose are: for passive devices—couplers (splitters, directional couplers), filters (Bragg, photonic crystals, etc.) and for active—lasers, amplifiers. As an example, a Mach-Zehnder interferometer is equal to two couplers.

We can now breakdown more complex devices, such as $N\times N$ AWGs, and calculate the equivalent number of elements $N_{eq}$ as $N_{eq}=2N(N-1)$. This is done by mapping the AWG into an equivalent network of 1×2 couplers. Fig.2 shows the evolution in integration density for photonics (rather than total number of elements). We have taken the data from (Granestrand *et al*., 1986; Gustavsson *et al*., 1992; Sasaki *et al*., 2005). With the metal optics described in the previous section, higher integration densities are possible in most cases, however, drastically lower optical losses are required.

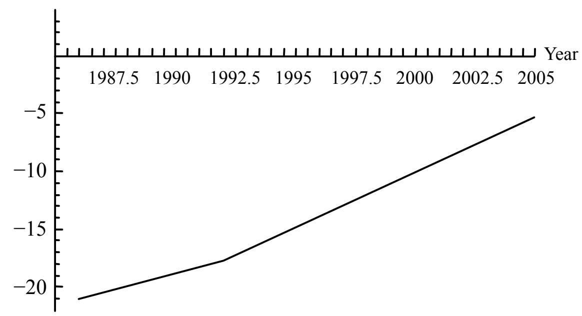


**Fig.2 A "Moore's law" for photonic lightwave circuit development, in terms of log to the base 2 of integration density in number of equivalent elements per μm$^2$ . Data from (Granestrand *et al*., 1986): 8×8 $LiNbO_3$ switch; from (Gustavsson *et al*., 1992): 4×4 InP gate array switch; from (Sasaki *et al*., 2005): Si wire arrayed waveguide grating, equivalent to 100 elements in 60×70 μm$^2$. The integration density exhibits nearly a doubling per year, faster than development in electronics**

## CONCLUSION

The feasibility of integrating photonic circuits with integration levels significantly higher than those possible with high contrast dielectric structures (including photonic crystals) was discussed and metal waveguides were identified as possible candidates.

Metal integrated photonic devices can generally be divided into two classes: Those with adequate performance using current materials, such as wavelength sized couplers (made possible by the fact that the loss per wavelength is comparable to that in the microwave case), and devices such as resonators, where much lower losses than those existing toady are required.

In the latter case, we derived formulae for the required lowering of loss levels or scattering rates in the Drude model.

We further formulated a photonics Moore's law and found that the integration density is nearly doubled each year, just like fiber optic transmission capacity. This is faster than Moore's law, but it only pertains to integration density. Regarding the total number of elements, we are still in the range of order 100, as was already demonstrated in (Granestrand *et al*., 1986). In principle, it should be possible to increase the total number of elements dramatically.

However, large improvements on the optical loss values in the metals are required, posing a challenging cross disciplinary research regarding the fundamental nature of scattering losses, mechanisms in free electron Fermi gases, and other pertinent media. A solution here would pave the way for a great increase in application of this type of photonics.

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