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Demonstration of Highly Efficient Waveguiding in a Photonic Crystal Slab at $\lambda = 1.5\mu m$ Wavelengths

S. Y. Lin, E. Chow

Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185

S. G. Johnson and J. D. Joannopoulos

Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract

Highly efficient transmission of 1.5 μm light in a two-dimensional (2D) photonic crystal slab waveguide is experimentally demonstrated. The light wave is shown to be guided along a triple-line defect formed within a 2D crystal and vertically by a strong index-guiding mechanism. At certain wavelength ranges, a complete transmission is observed. suggesting a lossless guiding along this photonic 1D conduction channel.

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The compact, lossless and broadband guiding of light is essential for building future large-scale optical integrated circuits (IC). Photonic crystal waveguides offer a new guiding mechanism that is fundamentally different from that of a traditional waveguide, based on total-internal-reflection. The introduction of line defects in a photonic crystal structure creates an optical channel for light to propagate [1]. If a line defect is properly designed, the resulting guiding mode falls within a photonic band gap and is highly confined. Because of its confining ability, a photonic band gap material may be viewed as a compact mirror for light guiding and bending. The guiding mode can also be designed to be broadband, and thus gives rise to a compact, broadband photonic crystal waveguide.

Early theoretical simulation suggests that lossless guiding and bending of electromagnetic waves is possible using a 2D or 3D photonic crystal [2-5]. Subsequently, a successful experimental demonstration of a 2D guide and bend was performed at millimeter wavelengths [6]. More recently, fabrication of a 1.5 μm 2D crystal waveguide was also reported [7]. However, there is no successful experimental demonstration of a perfect waveguiding in optical wavelength using either 2D or 3D photonic crystals. The main difficulty is that a pure 2D photonic crystal does not guide light well in the third direction, which leads to unavoidable loss caused by leakage.

This letter reports the experimental demonstration of efficiently guiding light at 1.5 μm wavelengths using a 2D photonic crystal slab. Light is shown to be guided along a 1D optical channel, defined by a triple-line defect formed within a 2D crystal slab. At certain wavelength ranges, a complete transmission is observed. This is the first experimental demonstration of lossless guiding in a photonic crystal at optical wavelengths.

The photonic crystal sample consists of triangular array of 2D holes, lithographically etched through a thin slab of GaAs. The hole array has a lattice constant a_0, and the hole diameter is $d = 0.6a_0$. This design gives a large photonic band gap [8]. The GaAs slab has an underlining 2 μm thick AlxOy layer and a thin SiO_2 layer on its top (see Fig.1(a)). The straight waveguide is created by introducing a triple-line defect in the direction of the ΓK symmetry. The diameter ($d' = 0.8\ a_0$) of defect holes is wider than that of the regular holes.

In Fig. 1(a), a SEM image of the side view of the fabricated sample is shown. The holes are periodic and the etched side walls straight, yielding a near perfect photonic crystal slab sample. In Fig.1(b), a SEM top-view image is shown. The conventional ridge waveguides located on either sides of the lattice are used for efficient coupling of laser light in and out of the photonic crystal section of the sample. The waveguides have a lateral width of 1.4 μm, which is well matched to the modal extend of triple-line defect. Nanofabrication of the sample is achieved using a combination of electron beam lithography and reactive ion beam etching. A more detailed fabrication process is described in Ref. [9-10].

Our photonic crystal slab guide has three unique features. One is that, contrary to the guiding principle of a conventional waveguide, it steers light in the lower index region. Second, the use of a slab design provides for a strong index guiding of light vertically even within the photonic band gap spectral region [8]. The third unique feature is that it is made of a triple-line defect, instead of the more straightforward single-line defect. Although a single-line defect also supports guiding mode, its center frequency is too close to the lower photonic band edge [11]. Any slight process variation may shift the guiding modes into the adjacent allowed band, and the guide becomes lossy. On the other hand, a triple-line defect structure has an effective index lower than that of a single-line defect, thus pushing the guided mode frequency away from the lower band edge and more into the band gap.

One potential drawback of the triple-line defect is that it is no longer single-mode, but instead has three guided modes. In Fig. 2, a theoretical calculation of the transverse electric (TE) field guided modes dispersion is shown as solid (even symmetry) and open dots (odd symmetry). The conduction band (CB), valence band (VB) and light-cone regions are also indicated as shaded lines. The three guided bands extend from 0.273 to 0.30, covering about 36% of the band gap. Experimentally, since the incoming laser light has an even symmetry, it can not be coupled into an odd mode. Taking this coupling consideration into account, a triple-line defect may in fact be treated as a single-mode waveguide.

To test the guiding efficiency and bandwidth of our photonic crystal guide, an in-plane transmission measurement is carried out. The laser light is TE polarized, coupled laterally into the input ridge waveguide (see Fig. 1b), transmitted through the triple-line defect, and then into the output ridge waveguide. The output light is then split and fed into a calibrated InGaAs photodetector and an infrared (IR) camera, respectively. In the inset of Fig.3, the modal profile image of output light at λ=1.550 µm, obtained from a 16 periods photonic-crystal waveguide (a=410nm), is shown. The observed image has a clean, round modal profile and is Gaussian-like. This indicates that the measured output signal does not derive from the undesired air mode or the substrate leaky mode [10]. Rather, it is a true measure of a well-confined photonic crystal guiding mode in the slab layer.

As the first step of the experiment, three spectra were taken from three different guiding samples, i.e. (i) a 2D hole array with a triple-line defect (see Fig.1b), (ii) a 2D hole array with no defect, and (iii) no 2D hole array and no defect (the reference spectrum). By ratioing spectrum-(i) to -(iii), an absolute guiding efficiency (η) of a triple-line defect is obtained. Similarly, by ratioing spectrum-(ii) to -(iii), the bulk transmttance (T) of the 2D slab hole array is obtained. In Fig. 3, η is shown as solid dots as a function of both λ and ω for a sixteen-period sample with a_0=410 nm. The guide has a high guiding efficiency and is broadband. Furthermore, at the fiber communication wavelength of λ ~ 1540-1565 nm, a perfect guiding efficiency is observed. This is the first demonstration of a complete guiding of light by a photonic crystal, 2D or 3D, in the optical wavelengths. For λ =1535-1575 nm, a $\eta > 70\%$ is observed. The slightly higher than 100% efficiency at certain frequencies suggests that a photonic crystal guide confines light better than that of the reference guide.

To map out the entire guiding efficiency spectrum, i.e. η vs. ω (= a_0/λ), both a_0 and λ are experimentally varied. To achieve this goal, a total of six samples is fabricated with a_0 = 400, 410, 430, 450, 460, 470 nm, respectively. Also, three laser modules are used to tune λ from 1290 nm to 1680 nm. This combination allows for a complete mapping of guiding efficiency throughout the entire photonic band gap regime. In Fig.4, the measured η and T are shown as red triangles and black circles, respectively. Also shown in Fig. 4 are the theoretically computed T (dashed line) and η (broken line), respectively. For T, the theory correctly predicts the transmission efficiency at both the CB and VB to within $\Delta\omega$ =0.01. In the band gap region, ω ~0.26 to 0.32, both the predicted line shape spectrum and intensity attenuation (T~ 10^{-3} - 10^{-4}) agree with experimental data. For η, highly efficient guiding starts from the lower frequency end (ω = 0.26) and extends into the mid-gap at ω ~ 0.29, consistent with the prediction of Fig. 2. Moreover, while photonic band gap attenuation is strong (T ~ 4 x 10^{-4}) at ω ~ 0.265, a near perfect η value of ~100% is observed. This correlation clearly demonstrates the strong guiding effect introduced by the formation of a triple-line defect and by the existence of a photonic band gap. The observed η also agrees with the computed curve, other than it extends slightly into the midgap by $\Delta\omega$ ~ 0.01. It is possible that the etched defect holes are slightly larger than the nominally designed d' =$0.8a_o$, and thus pushes the guiding mode more into the band gap.

To achieve an even wider bandwidth, guided modes need to be pushed further into the mid-gap. In principle, this can be done by further increasing the defect hole size to d' > $0.8a_o$. In practice, however, nanofabrication difficulty prevents us from doing so as the nearest hole-to-hole spacing will be too small, < 50 nm, for a reliable process control. One possible solution is to introduce a nonuniform, triple-line defect such that the middle line has a hole size of d' = $0.8a_o$+ Δd and the outer lines a d' = $0.8a_o$- Δd. As the guided mode electric field intensity concentrates mostly in the middle defect line, this arrangement effectively raises the guiding mode energy while maintaining the hole-to-hole spacing. Another way is to replace the GaAs slab with an AlGaAs slab. Upon slightly oxidizing the AlGaAs layer around the 2D holes, the effective index of the guiding modes can be made lower, thus raising the guiding frequency.

In summary, the design, fabrication and testing of a triple-line defect embedded in a 2D photonic crystal slab is reported. This new class of photonic crystal waveguide guides light in the lower index region, with a near perfect guiding efficiency at the optical communication wavelength of $\lambda \sim 1.5$ μm. Such a lossless guiding of light in a lower index region is a consequence of strong photonic confinement made possible by a photonic band gap.

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Correspondence and requests for materials should be addressed to S.Y.L. (e-mail:SLIN@sandia.gov)

Figure Caption

Fig.1(a) A cross-sectional SEM view of the fabricated triple-line defect embedded within a triangular array of holes. The defect holes have a larger diameter, d'=0.8 a_0, than the regular holes, d'=0.6 a_0. The holes are etched through a thin slab, 220 nm thick, of GaAs layer.

Fig.1(b) A SEM top view of the triple-line defect waveguide structure. The ridge waveguides are used to facilitate coupling of laser light in and out of the 2D slab hole array. Its width of 1.4 μm is designed to match the lateral modal extend of the triple-line photonic crystal waveguide.

Fig. 2 Computed TE dispersion of 2D photonic crystal slab waveguide. The three guided bands extend from 0.27 to 0.30, covering about 36% of the band gap. The conduction band, valence band and light-cone regions are indicated as shaded lines.

Fig. 3 Absolute guiding efficiency, η, plotted as a function of λ. At the communication wavelength of $\lambda \sim$ 1540-1565 nm, a perfect guiding efficiency is observed. In the inset, the infrared image of transmitted output light at λ=1.550 μm is shown.

Fig.4 Absolute guiding efficiency (η) and transmittance (T) plotted as a function of ω over the entire photonic band gap region.

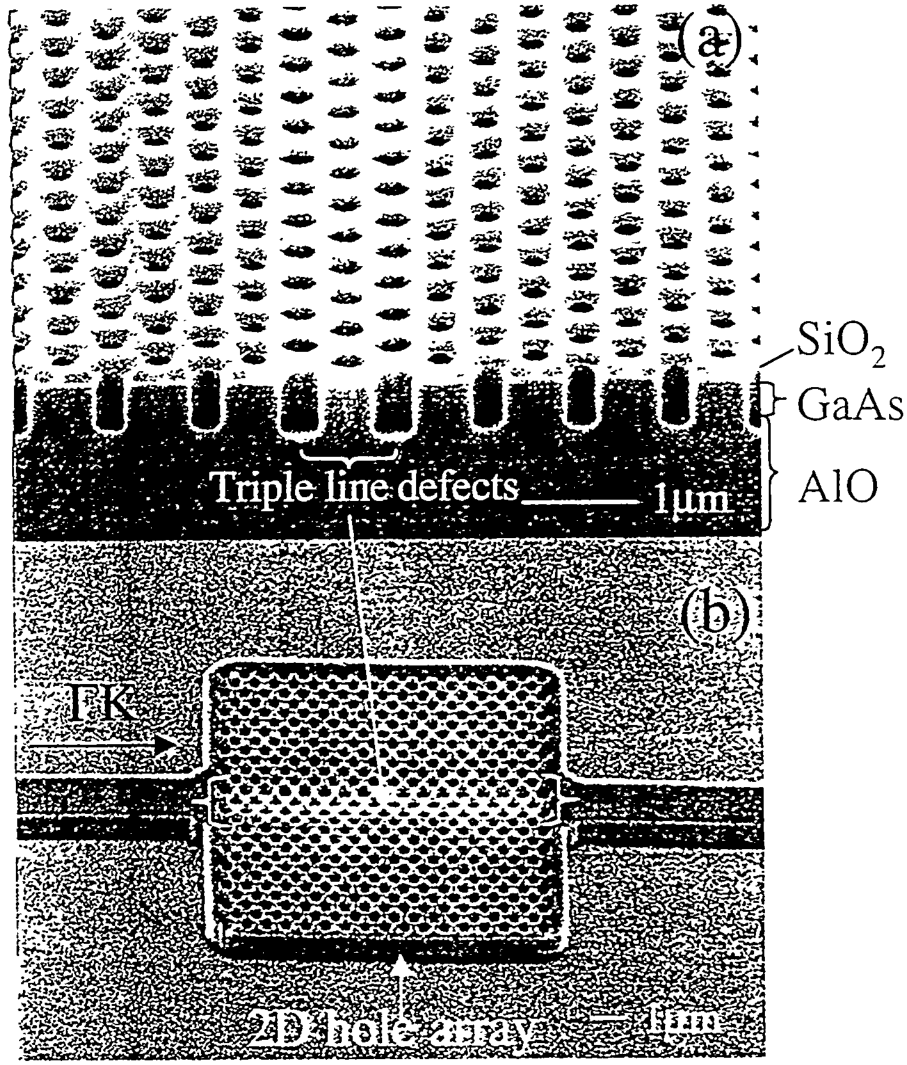


Fig.1

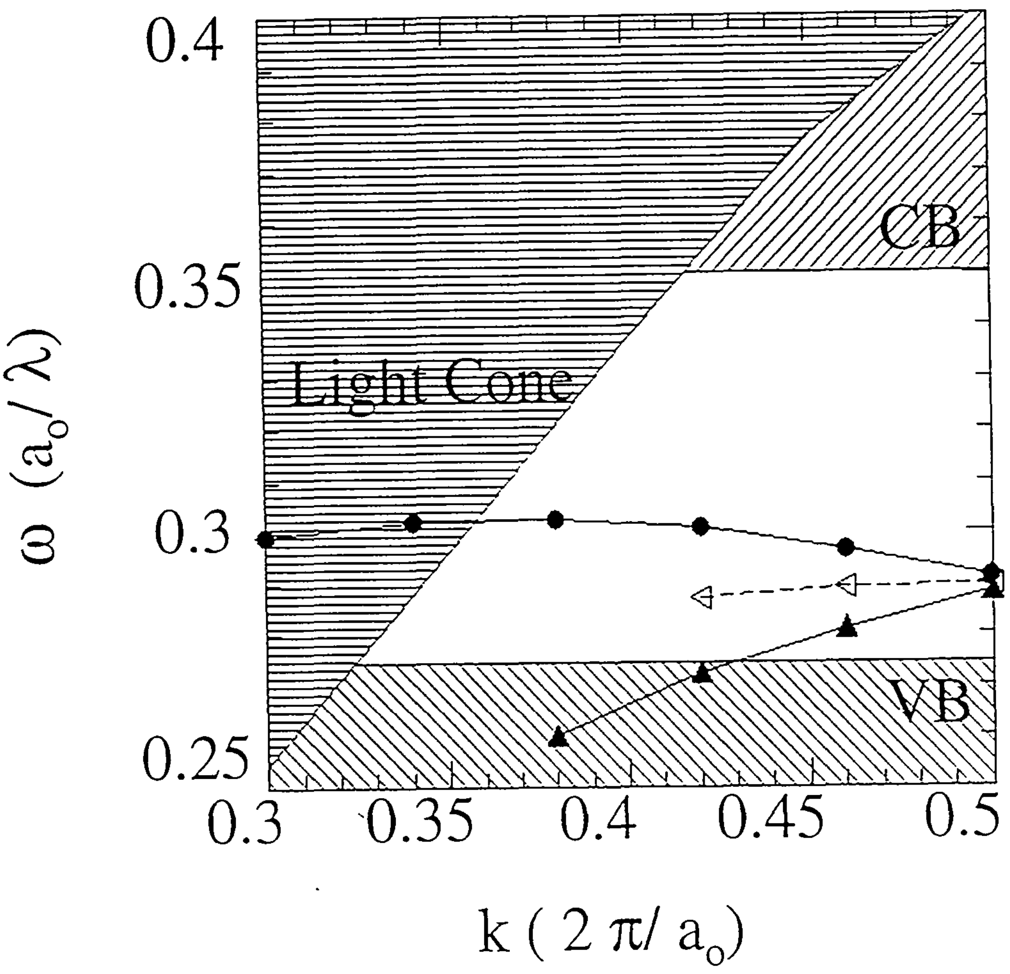
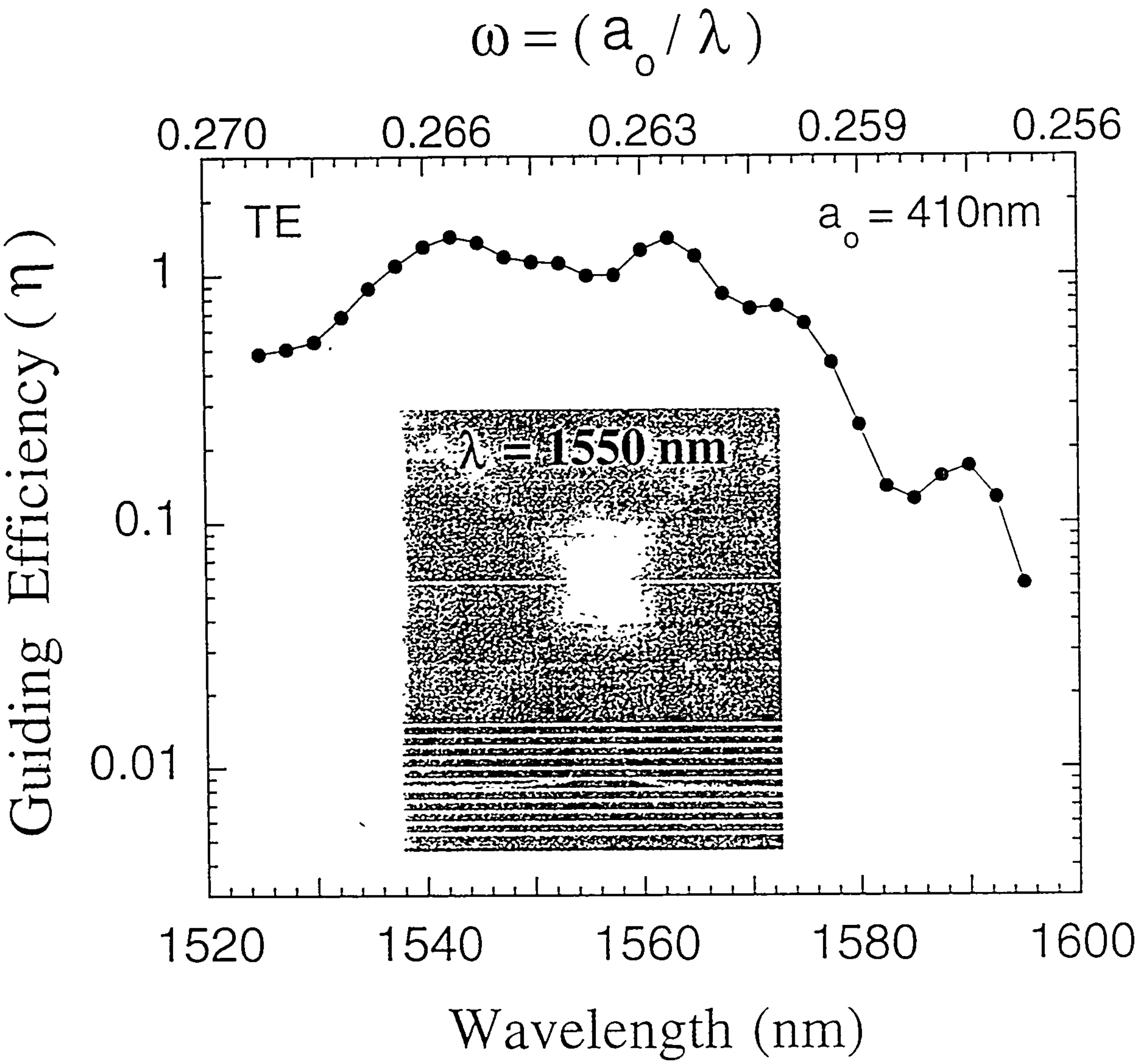

0.4
0.35
0.3
0.25
CB
Light Cone
VB
ω (a_o/λ)
0.3
0.35
0.4
0.45
0.5
k (2 π/ a_o)

Fig. 2



ω = (a
o
/ λ)
0.270
0.266
0.263
0.259
0.256
TE
a
o
= 410nm
λ = 1550 nm
1
0.1
0.01
Guiding Efficiency (η)
1520
1540
1560
1580
1600
Wavelength (nm)

Fig. 3

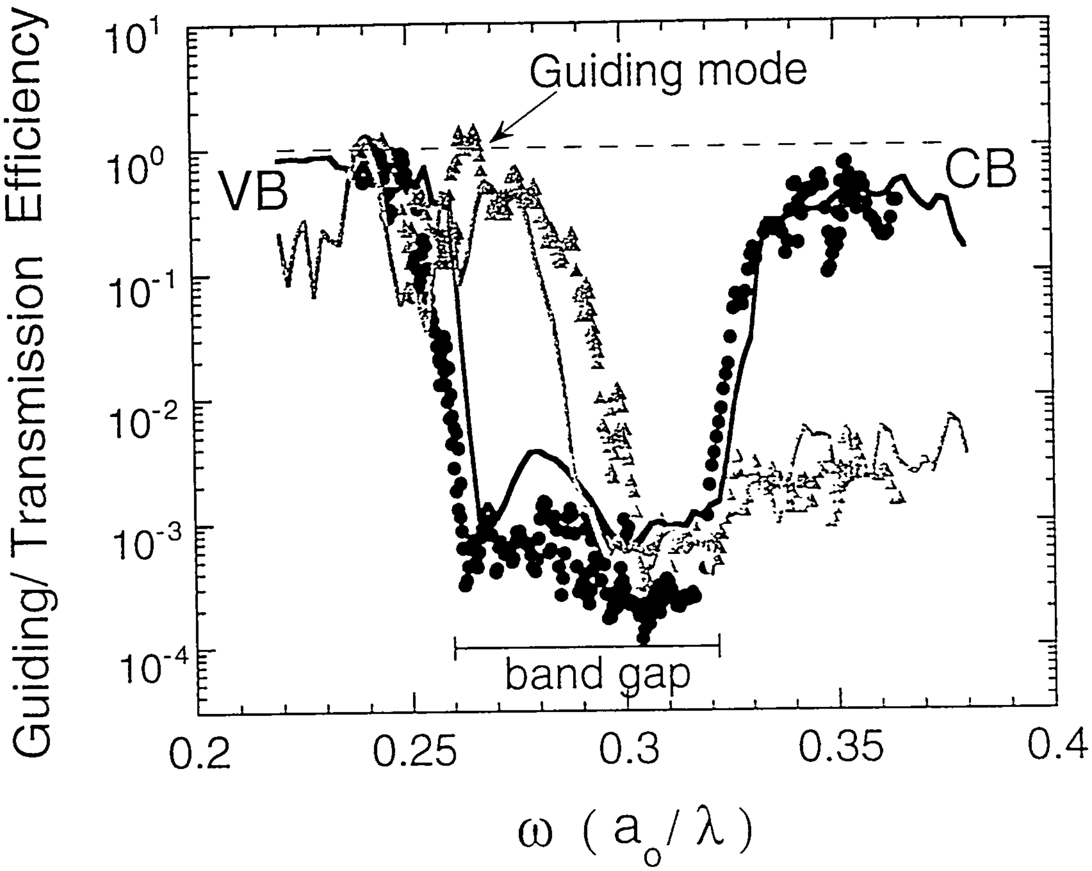

Guiding/ Transmission Efficiency
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Guiding mode
VB
CB
band gap
0.2
0.25
0.3
0.35
0.4
ω (a_o / λ)

Fig. 4