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Title:

# Observation of optical amplification excited by traveling electron beam

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Abstract:

Amplification of optical light excited by traveling electron in the vacuum environment was firstly observed in the near infrared optical region as a Cherenkov-type amplifier. The light whose wavelength is 1.5μm propagated in a Si-$SiO_2$ dielectric waveguide. The accelerated voltage of the electron beam for the amplification was around 42kV. Dispersion relation between the wavelength and the acceleration voltage well coincided with theoretically calculated results.

KEYWORDS:

optical amplifier, unidirectional amplifier, traveling wave, electron beam, traveling electron, vacuum, waveguide, Cherenkov laser

Conventional lasers are utilizing energy levels of material to get the stimulated emission. Operating wavelength of these lasers is characterized with the laser material. Identical optical gain is supported for both forward and backward propagating waves in these lasers. On the other hand, the traveling wave tube[1], the free electron laser[2] and the Cherenkov laser[3] are devices to emit or amplify electro-magnetic wave by traveling electrons in wide frequency range only for forward wave. One of the authors had theoretically proposed a scheme to realize unidirectional optical amplifier utilizing a dielectric waveguide and an electron gun in vacuum environment[4] as a Cherenkov-type amplifier. Additional precise theory was also followed[5].

Configuration of the device is illustrated in Fig.1. The optical waveguide (O.W.) consists of a higher and a lower refractive index layers to be the core and the cladding layers, respectively. The optical field propagates through this waveguide and partly penetrates into the vacuum region in form of the evanescent wave. The phase velocity of the optical field $v_{opt}$ is given with the equivalent refractive index $n_{eff}$ to be

$$v_{opt} = c/n_{eff} \quad . \tag{1}$$

The electron beam is emitted from an electron gun with acceleration voltage $V$ and travels with velocity $v_e$ along surface of the waveguide. The relativistic energy of the electron is $m_o c^2/\sqrt{1-(v_e/c)^2} = m_o c^2 + eV$, where $m_o$ is the rest mass of the electron. Then, the electron velocity $v_e$ is given by

$$v_e = c\sqrt{1-1/(1+eV/m_o c^2)^2} \quad . \tag{2}$$

Conditions to get optical amplification are as in followings [4]:

1. The velocity of the electron $v_e$ should be slightly higher than the velocity of the optical light $v_{opt}$.
2. Electric field component of the optical light should exist along the propagation (longitudinal) direction. That is, TM (transverse magnetic) mode is suitable in this waveguide structure.

Experimental set up is shown in Fig.2. An electron gun was installed in a vacuum chamber. The acceleration voltage varied from 30kV to 50kV. The emission current was about 0.05mA. Rig type optical waveguide (O.W.) was formed by etching Si layer of the SOI substrate which consists of Si-SiO$_2$-Si layers. The top Si layer is the core layer with stripe width of 50 to 100μm. The SiO$_2$ layer works as the cladding layer whose thickness of 1.0μm is thick enough to prevent field penetration into the bottom Si. Etched surface was covered with Al film to release charged electrons to the earth. The waveguide consists of two straight portions and a curved corner. One of the straight portions is for introduction of the incident light. Another portion is for the amplification and length of the portion is 5mm. The waveguide sample was set on a mechanical manipulator in the camber. The incident light was introduced from a tunable laser operating around 1.5μm through single mode optical fibers and a fiber-polarization controller. Output light from the waveguide was detected through a view port and a polarizer. The polarization controller and the polarizer were used to select polarization of the guided light.

Optical field distribution in the waveguide and the effective refractive index $n_{eff}$ were theoretically calculated. Penetrating depth of the optical field into the vacuum region was estimated to be in order of 0.1μm. On the other hand, cross-sectional size of the electron beam in our experiment was around 200μm. Then, the electron beam had to touch to surface of the waveguide, which brought several troubles such as charging up the waveguide with electrons and piling up contamination on the waveguide.

To relax these troubles, we deflected position of the electron beam by pulsed current applied on the deflecting coil in the electron gun. Figure 3 (a) and (b) are time traces of the output light from the waveguide and pulsed current to the deflecting coil. Rectangular pulses with 1.6 ms width indicate the current to the deflecting coil, during which the electron beam runs along surface of the waveguide touching on the surface. The electron beam was removed from the waveguide in other time range. Figure 3(a) is the case that the optical light was not amplified. The output light was decreased by touching the electron beam on surface of the waveguide. We found here that decrease of the light has a time delay of almost 1 ms. This delay may come from to charge up whole of the waveguide. Figure 3(b) is the case that the optical light increased just after applying the pulse current then decreased. Amount of the decrease was smaller than the case of Fig.3(a). The increased portion in Fig.3(b) must be evidence of the optical amplification by proposed scheme.

Such amplification critically depend on the acceleration voltage $V$ and wavelength $\lambda$ of the light. Figure 4 shows mapping of the data with circles where amplifications such as Fig.3(b) were observed for samples whose core thicknesses are d=0.315 and 0.320μm. The lines are theoretically calculated characteristics to satisfy $v_e = v_{opt}$ from eqs.(1) and (2), whose condition is called the resonance condition between the electro magnetic field and the traveling electron. The experimental data well fit with the theoretically calculated lines. The increasing of the optical intensity in Fig.3(b) was 0.1 to 0.3 % which corresponds to the amplification gain coefficient of $g=0.2$ to $0.6m^{-1}$. Direct comparison of this value to the theoretically predicted value in Ref.4 is not easy, because we do not know some important parameters such as the interaction length between the electron beam and the optical field. The amplification were never observed for TE (transverse electric) mode of optical light.

Our next subject is to increase the optical gain by focusing the electron beam with an electron lens.

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## Figure Captions

Fig.1 Schematic illustration of an optical amplifier excited by traveling electron beam.

Fig.2 Experimental set up.

Fig.3 Time traces of the output light and the deviating voltage.

(a) is the case without optical amplification.

(b) is the case that the output light is amplified.

Pulsed current with 1.6 ms width were applied to deflecting coil to run the electron beam along surface of the waveguide during this interval. The output light decreased in (a) but increased just after applying the pulse in (b).

Fig.4 Dispersion relation between the electron acceleration voltage and the wavelength of the light.

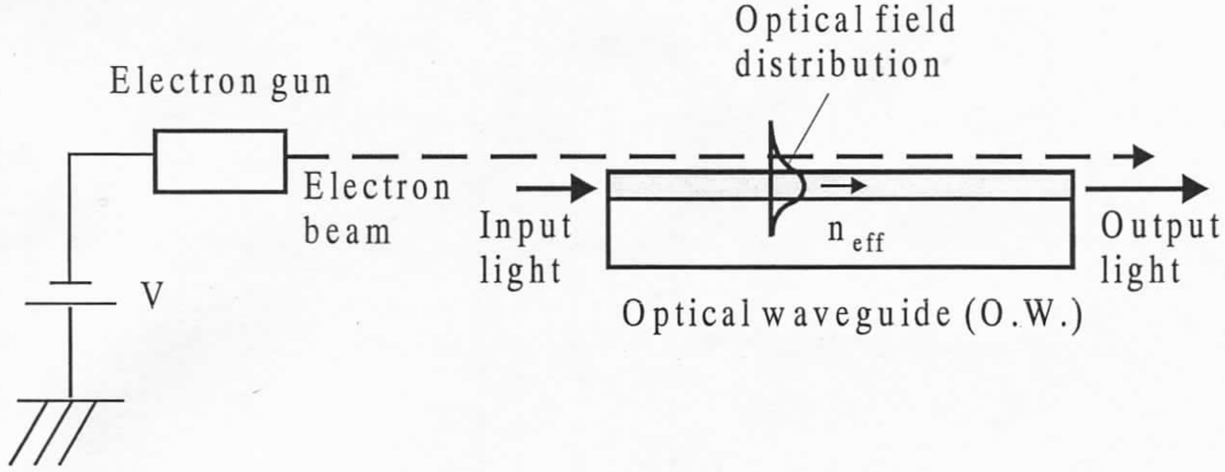


Fig.1。 Y.Kuwamura et.al

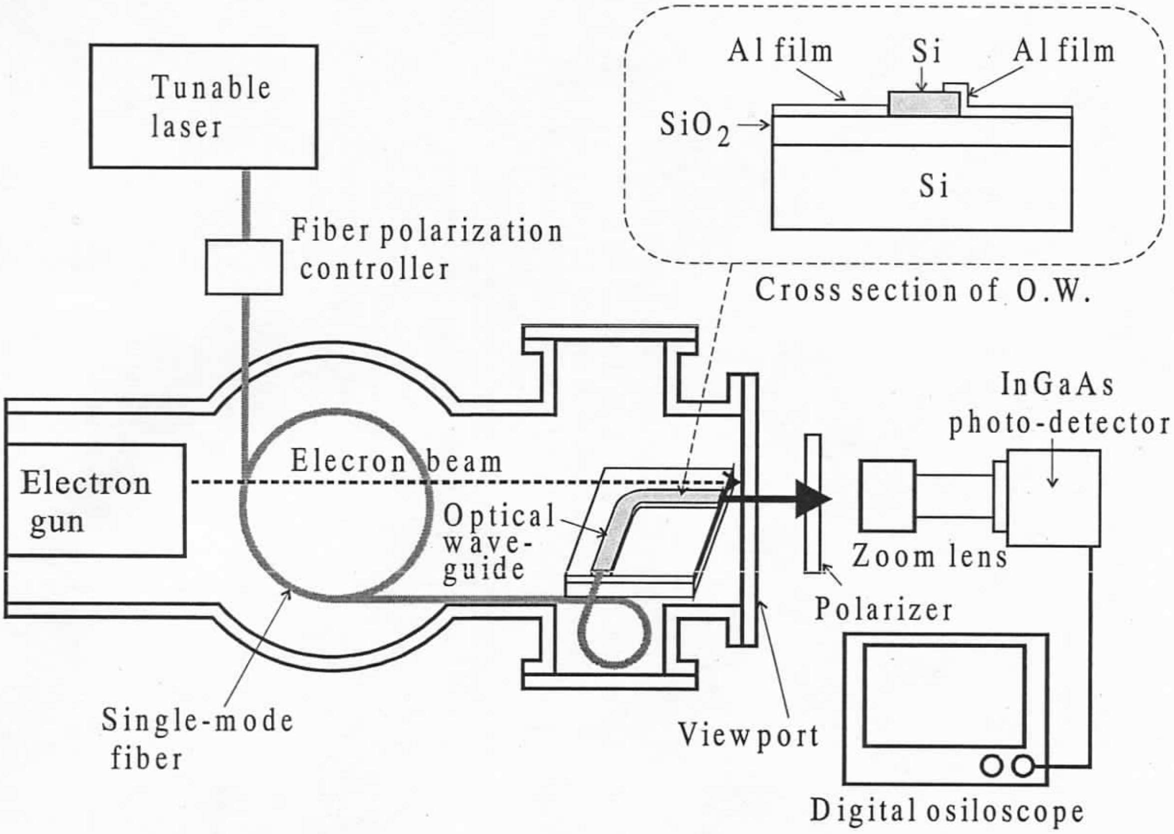
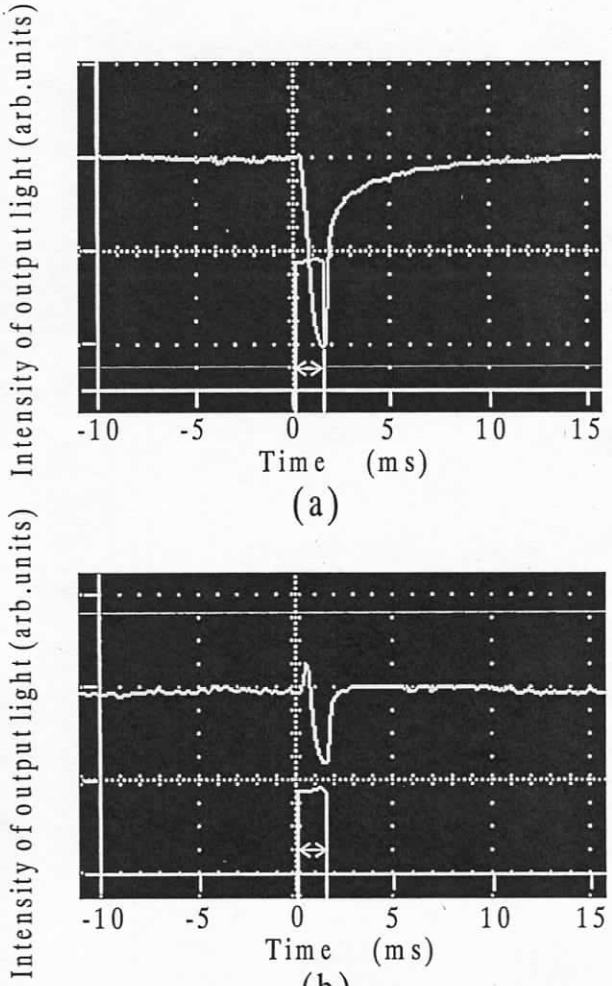


Fig.2. Y.Kuwamura et.al



(a)

(b)

Fig.3. Y.Kuwamura et.al

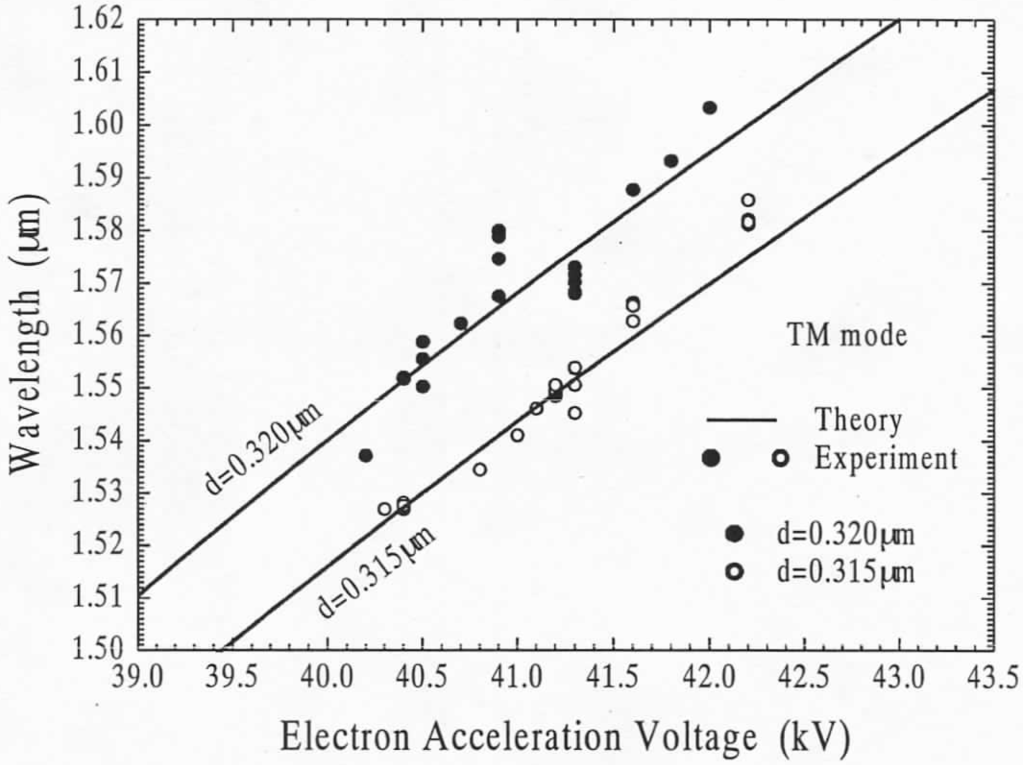


Fig.4 Y.Kuwamura et.al