where v( 0, t ) is the modulation voltage at the input end x = 0, $\omega=2\pi f$ is the angular frequency, $\alpha$ is the attenuation constant, $\beta$ is the phase constant, $V_\pi$ is the half-wave voltage, $\lambda$ is the light wavelength, s is the gap spacing, $\gamma_{33}$ is the electrooptic coefficient, $\Gamma$ is the overlap integral between optical and microwave fields, $N_0$ is the refractive index of lightwave, L is the coupling length, $\theta$ is the difference of the electrical length between optical and signal waves, c is the light velocity in free space, and $N_m=c/(\omega/\beta)$ is the effective refractive index of the signal wave.

In this case the intensity of the optical power at the output end of the Mach-Zehnder optical modulator is given by

$$I = I_0 \cos^2\left(\frac{\Delta\phi}{2}\right) \tag{8}$$

where $I_0$ is the maximum output power in the absence of modulation voltage, i.e., $\Delta\phi=0$.

The variable $F(\omega)$ given by Eq. (6) is proportional to the amplitude of the optical phase difference, which is referred to as the normalized modulation depth. This is an important variable which determines the bandwidth of the modulator through the frequency characteristics of $\theta$ and $\alpha$.

In the case of velocity matching between the optical wave and the signal wave, i.e., $N_0=N_m$, Eq.(6) leads to the expression for the modulation depth as

$$F(\omega) = \frac{1-e^{-\alpha L}}{\alpha L} \tag{9}$$

In this case, the frequency dependence of $F(\omega)$ originates from that of $\alpha(f)$. From Eq.(9) we can define the optical 3 dB bandwidth $\Delta f$ by the frequency which gives $F(\omega)= 1/2$. This gives the relation

$$\alpha(f)L = 1.59 \tag{10}$$

Taking into account that the attenuation constant consists of conductor loss and dielectric loss, and that the conductor loss is proportional to the surface resistance, we assume the frequency dependence of the attenuation constant to be given as

$$\alpha_n(f) = \alpha_{cn0} f^{1/2} + \alpha_{d0} f \tag{11}$$

$$\alpha_s(f) = \alpha_{cs0} f^2 + \alpha_{d0} f \tag{12}$$

where $\alpha_n$ and $\alpha_s$ represent the attenuation constant of the normal-conductor and the superconductor, respectively, $\alpha_{cn0}$ and $\alpha_{cs0}$ are proportionality constants for conductor loss and $\alpha_{d0}$ is the proportionality constant for dielectric loss. Equations (10), (11) and (12) give the expressions for the bandwidths as

$$\Delta f_n = 0.25\left(\frac{\sqrt{6.36\alpha_{d0} + \alpha_{cn0}^2 L}}{\alpha_{d0}\sqrt{L}} - \frac{\alpha_{cn0}}{\alpha_{d0}}\right)^2 \tag{13}$$

$$\Delta f_s = 0.795\left(\frac{1.59\sqrt{\alpha_{cs0} + 0.157\alpha_{d0}^2 L}}{\alpha_{cs0}\sqrt{L}} - \frac{0.629\alpha_{d0}}{\alpha_{cs0}}\right) \tag{14}$$

where $\Delta f_n$ and $\Delta f_s$ are the bandwidth for the normal-conductor and the superconductor, respectively.

In Fig.2 we show the cross-sectional view of the optical modulator with coplanar waveguide and a shielding plane. It is shown that the conditions for velocity matching and impedance matching are satisfied for w1=8[μm], s=15[μm], d=1.8[μm], h1=h2=0.5[μm], h3=5.5[μm].

In Fig.3 we show the threshold voltage calculated from Eq.(5) as a function of coupling length L. In the calculation we used the values for the parameters: $\lambda$=1.55[μm], $N_0$=2.15, $\gamma_{33}=30.8\times10^{-12}$[m/V], $\Gamma$=0.867. We see that the threshold voltage, i.e., modulation power, is decreased as L increases.

In Fig.4 we show the optical 3 dB bandwith as function of coupling length L calculated from Eqs.(13) and (14). In the calcultaion we used the values for the attenuation constants: $\alpha_{cs0}=1.63\times10^{-5}$[dB/cm · GHz$^2$] for Nb, $\alpha_{cs0}=2.16\times10^{-4}$[dB/cm · GHz$^2$] for YBCO, $\alpha_{cn0}$=0.43[dB/cm · GHz$^{1/2}$] for Au given in [2], $\alpha_{d0}=7.4\times10^{-3}$[dB/cm · GHz] corresponding to the loss tangent of LN as $\tan\delta$=0.005.The attenuation constants for superconductors are estimated by numerical calculations described in [13] using the complex conductivity for the superconductors $\sigma=\sigma_1-j\sigma_2$, where $\sigma_1$ is the conductivity due to normal-conducting current and $\sigma_2=1/\omega\mu_0\lambda_L^2$ ($\lambda_L$:magnetic penetration depth) is the effective conductivity resulted from superconducting current. In the present simulation we used the following experimental values: $\lambda_L$=0.2[mm] for YBCO, $\lambda_L$=0.05[mm] for Nb, $\sigma_1=4.01\times10^6$ [S/m] and $\sigma_2=2.57\times10^7$ [S/m].

In Fig.5 we show the figure of merit of the modulator,i.e., $\Delta f/V_\pi$ as a function of the coupling length. It is shown that for superconductors the figure of merit increases as the coupling length increases.

In Fig.6 we show the waveforms of a rectangular pulse with the width of 20ps traveling in various conductors which was calculated from Eqs.(1)-(3),(11) and (12). It is shown that waveform decays greatly as the attenuation constant increases.

In Fig.7, we show the waveforms of the optical output waveforms calculated from Eqs.(2)-(7) in the case of velocity matching for various conductors. It is shown that the optical output decreases as the attenuation increases.

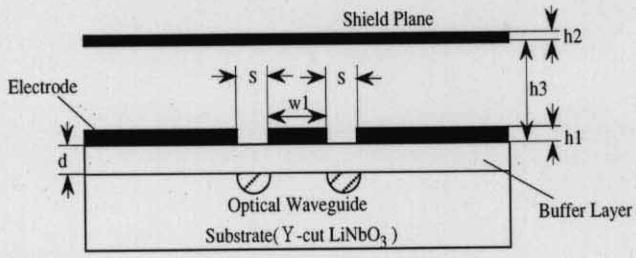


Fig.2 coplanar waveguide with a shielding plane

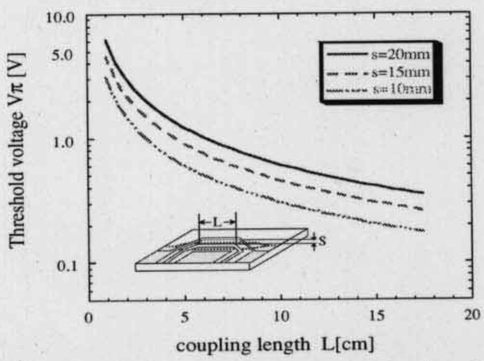


Fig.3 Calculated threshold voltage $V\pi$ as a function of coupling length L