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Thin film lenses for surface acoustic waves and their application to filters

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1. Introduction

The effect of diffraction on a Surface Acoustic Wave (SAW) filter is usually analyzed on the assumption that the waves are everywhere propagating on a free surface of substrates, known as free-surface diffraction. However, because of the perturbation effects of an interdigital transducer (IDT), such things as the shorting of electric field accompanying SAW and mass loading, the phase velocity is lower under the transducer than it is elsewhere. The IDT behaves as a $\Delta v/v$ waveguide, and these waveguiding effects cannot be neglected as the length of the transducer is increased and the width is reduced. By considering the IDT as the waveguide, a transversely weighted uniform IDT, which preferentially excites the fundamental guide mode, has been proposed.¹⁾ However, the transversely weighted IDT has such a disadvantage that the electrode fingers of the IDT become thinner. In this report, we propose a new type of filter, employing thin metal film lenses which vary the transverse amplitude distribution of SAW at the incident end of IDT, so as not to couple all the higher guide modes except the fundamental mode.

2. Design and analysis of lenses

Figure 1 schematically shows the basic configuration of a filter with thin metal film lenses between a launching transducer, IDT₁, and a receiving transducer, IDT₂. The shapes of these lenses are determined so that the transverse amplitude function of a SAW launched by IDT₁ becomes almost the same as that of the fundamental guide mode at the incident end of IDT₂. The lenses can be designed approximately by using a ray model. As shown in Fig. 2, let's consider a ray that leaves point A(0, y) on the y-axis, which is the incident end of the convex lens, and travels parallel to the x-axis. After passing through the lenses, the ray reaches point D(D_r, Y) at the outgoing end of the concave lens. The ray is refracted at points B(x, y) and C(X, Y). By ensuring that the ray satisfies Snell's law of refraction, and that the propagation phase delay

between the points of A and D is constant when y is varied, we can obtain following equations

$$\frac{dx}{dy} = -\frac{y-Y}{\sqrt{C_0^2 + C_1(y-Y)^2}}, \quad y = \int_0^Y f(y') dy' \quad (1)$$

$$X = x - \frac{C_0 V_f}{C_1 V_m} + \frac{\sqrt{C_0^2 + C_1(y-Y)^2}}{C_1} \quad (2)$$

$$C_1 = \frac{V_f^2}{V_m^2} - 1 \quad (3)$$

where V_f and V_m are the SAW phase velocity on the free surface and the metalized surface, respectively. $f(y)$ is the power flow density function of SAW at $x=D_r$, and C_0 is a constant corresponding to the propagation phase delay. In Fig. 2, the solid curves are the lens profiles obtained from Eqs. (1)~(3) under the condition that the lens width is of 20λ (λ represents the wavelength for SAW propagating on a metalized sur-

Fig. 1 Schematic of a SAW filter with lenses.

Fig. 2 Lenses and design model, using a ray model.

Fig. 3 Subdivided lens for wave theory analysis.

face), $D_t = 40\lambda$, $f(y) = \pi \cos(\pi y/W)$, $(V_t - V_m)/V_t = 0.0275$ and the thickness of both ends of the convex lens is almost reduced to zero.

The ray theory holds true when the SAW, launched by IDT₁, can be considered to be a plane wave. However, for a narrow beam width, as shown in Fig. 2, good results may not be obtained from the ray theory. Therefore, in addition to the ray model design of the lenses mentioned above, it is necessary to analyze the lens properties in terms of wave propagation theory.

Divide the lenses along the propagation direction into a number of intervals shorter than a wavelength, as in Fig. 3. In each intervals, it is theorized that the SAW propagates with little diffraction spreading. Take, for example, the propagation from $x = x_{n-1}$ to x_n . The SAW emanating from the aperture of $|y| < y_n$ propagates almost only on the metalized region, while the SAW of $|y| > y_n$ propagates almost only on the free region. Due to this fact, it can be assumed that the following approximate solutions hold true in the each intervals.

$$\phi(x_n, y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi_m^{(n-1)}(k_y) e^{-j(k_{xm} \Delta x + k_y y)} dk_y + \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi_f^{(n-1)}(k_y) e^{-j(k_{xf} \Delta x + k_y y)} dk_y \quad (4)$$

where $\phi(x_n, y)$ is the amplitude of SAW at point (x_n, y) . The first and second terms of the right hand side, which are derived from scalar wave equations, are the solutions for the SAW emanating from the region $|y| < y_n$ and $|y| > y_n$, respectively. And

$$k_{xm}^2 = \left(\frac{\omega}{V_m}\right)^2 - k_y^2, \quad k_{xf}^2 = \left(\frac{\omega}{V_f}\right)^2 - k_y^2 \quad (5)$$

$$\Phi_c^{(n)}(k_y) = \int_c \phi(x_n, y) e^{jk_y y} dy, \quad (c = m, f) \quad (6)$$

$\int_m$ and $\int_f$ express the integration over $|y| < y_n$ and $|y| > y_n$, respectively. Equation (4) is the angular spectrum representation²⁾ including the velocity reduction effects due to the metallization pattern. Including velocity anisotropy, Eq. (4) can be used to calculate the amplitude of the SAW on an anisotropic substrate.

In order to verify the validity of the approximate

Fig. 4 Calculated transversal amplitude at 40λ of propagation distance in a uniform $\Delta v/v$ waveguide (solid lines: approximate, dotted lines: exact).

Fig. 5 Calculated transversal amplitude after passing through lenses (dotted: fundamental guide mode amplitude).

solution, Eq. (4), the numerical calculation of the amplitude is performed for a waveguide of uniform width, excited by an idealized line source parallel to the y direction. Figure 4 shows the amplitude distribution at a propagation distance of 40λ from the source. The width of the guide is 20λ and the length of the source is 20λ . In Fig. 4, two kinds of curves are compared. The solid lines represent the results of the approximation solutions which are computed by using FFT algorithm (2,048 data points and $\lambda/8$ sampling point spacing, $\Delta x = \lambda/4$). The dotted lines are the exact solutions based on an optical waveguide theory,³⁾ where the boundary conditions are taken to be that the amplitude and its transverse derivative are continuous at the interface between metalized and free regions. There is excellent agreement between the approximate and the exact solutions.

Figure 5 shows the amplitude distribution (solid lines), calculated from the approximation solutions for SAW launched from a line source with a length of 20λ and passing through the lenses of Fig. 2. Large ripples exist, due to diffraction, on the magnitude of the amplitude. Ignoring these ripples, the amplitude of the

Fig. 6 Experimental response of test filters (solid line: for filter with lenses, dotted line: filter without lenses).

SAW agrees approximately with the amplitude of the fundamental mode of a waveguide with a 20λ width (corresponding to IDT_2). The phase is almost constant across the aperture of IDT_2 . However, it should be noticed that the shapes of lenses are determined by using the power flow density function, $f(y)$ which is not equal to the power flow density function of the fundamental mode. This also means that the works of lenses on SAW beam shaping, which is produced by refraction, are affected by diffraction.

3. Experiment

Test SAW filters with and without lenses were fabricated on 128° rot. YX $LiNbO_3$ substrate to evaluate the availability of lenses. The launching IDT has 5 finger pairs. The apodized receiving IDT has 40 finger pairs. The apodization function is a Hamming function that is compensated according to the fundamental mode amplitude function which is obtained by means of a scalar potential model for an anisotropic substrate.^{4,5)} The overall aperture is 20λ and the width of the bus bar is 1λ . For the design of lenses on $LiNbO_3$, Eqs. (1)~(3) cannot be used, due to the fact that these equations hold true only in the case of lenses on an isotropic substrate. Lenses with a similar shape of these in Fig. 2 are used by trial and error. The thickness of both lenses are 17.5λ . Figure 6 shows an example of the measured responses of the filter. The

maximum level of the sidelobe in the filter with lenses is about -38 dB which is 5 dB higher than the ideal response of a filter with a Hamming weighted IDT. However, the sidelobes in the filter with lenses are clearly lower than in the filter without lenses. From this result, it can be presumed that the fundamental waveguide mode of the IDT is preferentially excited by use of lenses.

4. Conclusion

It has been demonstrated that convex and concave shaped thin metal film lenses can be used to excite the fundamental guide mode of the IDT preferentially. By using such lenses, it becomes easy to design a SAW filter, because a SAW propagates under the electrode without varying the transverse amplitude profile.

Additionally, the approximate approach for the wave analysis of SAW propagation through lenses presented in this letter is extended to an anisotropic substrate in combination with the angular spectrum of waves technique. This approach is also applicable to an analysis of SAW devices with metal films on a propagation path, such as a horn beam compressor in a SAW convolver.

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