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Advanced 2D Periodic Array and Full Transversal Mode Suppression

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***Abstract*— In this work, we present an improved version of the 2D periodic array from [Yoon et al, IUS2012, [1]]. Using a 2D P-matrix simulation tool, required COM (coupling of modes) parameters and periodic $\Delta v/v$ waveguide parameters were optimized for desired 2D behavior. On this basis, the fine-tuned real geometries were determined. In the analysis of such a resonator, we introduce a novel approach in analogy to a multiple quantum well structure in solid state physics. It turns out that the optimized 2D periodic array with geometry variations fully suppresses all unwanted transversal modes within a certain bandwidth. Besides, prominent peaks by the transversal periodicity are also distinctively suppressed at the frequencies where the wavelength of the y-components of the transversal modes is comparable to the transversal pitch (p_T), i.e., near $k_y = \frac{\pi}{p_T}$. Therefore the 2D periodic array on the electrodes can be readily employed in designing SAW filters in SiO_2-covered $LiNbO_3$ with excellent performance.**

***Keywords*— SAW, Waveguide, Periodic Array, Full Transversal Mode Suppression**

I. Introduction

Typically, a one-port resonator in SiO_2-covered $LiNbO_3$ displays a series of distinct transversal modes above the resonance frequency. When such resonators are used in filter designs without taking any countermeasures, the transversal modes lead to unacceptable passband ripples[2], [3]. In the previous work [1], we have demonstrated that a 2D periodic array with patches on electrodes can successfully get rid of undesired modes within the frequency band of $k_y = \left[0, \frac{\pi}{p_T}\right]$, where p_T is the transversal pitch of the periodic array. However, the resonator exhibits strong conductance at frequencies, where the wavelength of the y-components of the transversal modes is comparable to transversal pitch of the patches. We now entitle the phenomenon as “Transversal Resonance”. Therefore the major challenge using 2D periodic arrays with patches is to suppress or avoid the transversal resonance.

In this work, we have conducted further investigation on 2D periodic arrays from [1] in order to minimize the transversal resonance while fully suppressing all unwanted transversal modes. At the initial step, simulations were performed utilizing the well established 2D P-matrix model. In this model, a unit cell is defined with two strips, which then is infinitely cascaded taking into account reflection and diffraction[4], [5]. Using those simulations, the fine-tuned real geometries were determined. Measured and simulated admittances of resonators are in good agreement.

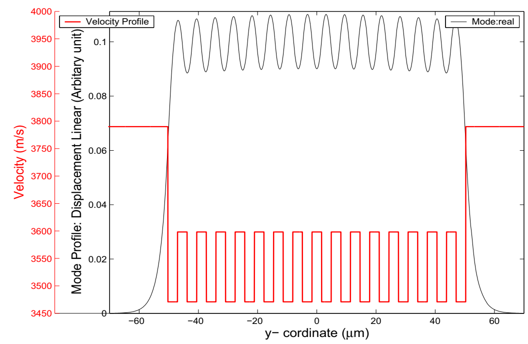


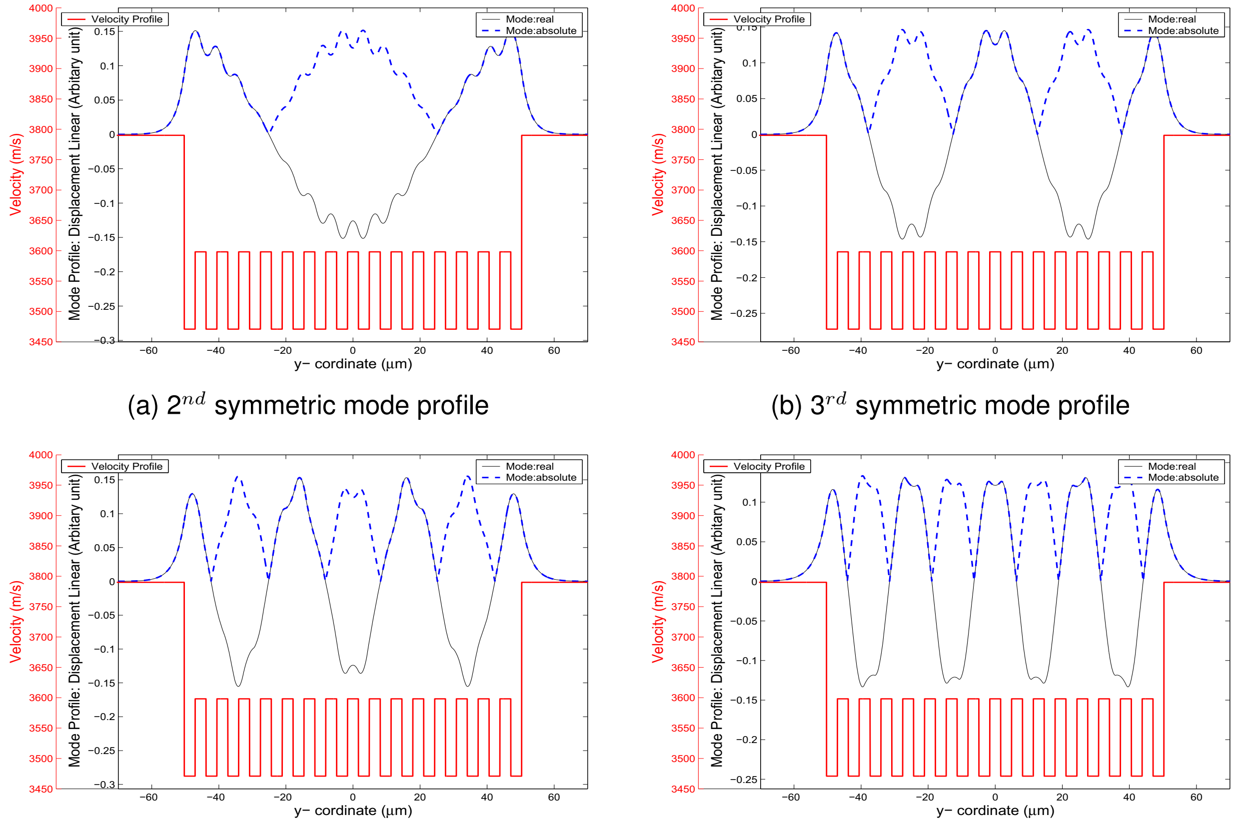
Fig. 1. The required fundamental mode with the $\Delta v/v$ waveguide profile. The used velocity in the figure is the undisturbed (or center) one, where the effect of reflection is not taken into account, and the mode profile is from the simulation. Note that it is a simplified schematic of the $\Delta v/v$ waveguide.

II. Principle of Mode Suppression

It is shown that, if the transversal pitch of the patches is equal to the wavelength of the y-component of a transversal mode, the corresponding transversal mode profile becomes cosine-like (or envelope-like), which means that the upper and lower displacements are unequal. Consequently, the resulting values of the overlap integral for those modes increase and give rise to sharp peaks in the resonator’s frequency response. Therefore, in order to suppress the peaks, one should shape the favourable mode profiles such that the upper and lower displacements are equal.

We now summarize the principle of the undesired transversal mode suppression as follows;

i) Shape the fundamental (=first symmetric) mode profile such that the overlap integral (Eq. 1) of it is maximized (Fig. 1).
ii) Shape the higher symmetric mode profiles such that the



(a) 2^{nd} symmetric mode profile

(b) 3^{rd} symmetric mode profile

(c) 4^{th} symmetric mode profile

(d) 5^{th} symmetric mode profile

Fig. 2. The required higher symmetric modes with the $\Delta v/v$ waveguide profile. The used velocity in the figure is the undisturbed (or center) one, where the effect of reflection is not taken into account, and the mode profile is from the simulation. Note that it is a simplified schematic of the $\Delta v/v$ waveguide.

areas of upper and lower displacements are equal and, consequently, the corresponding overlap integrals are minimized (Fig. 2) .

Here, the overlap integral(or excitation strength) is the scalar product of the excitation profile and k^{th} mode profile over the transversal direction ([6]), i.e.,

$$E^k = \langle e(y)|\psi^k(y)\rangle = \int_{-\frac{A}{2}}^{\frac{A}{2}} e(y)\cdot\psi^k(y)dy, \qquad (1)$$

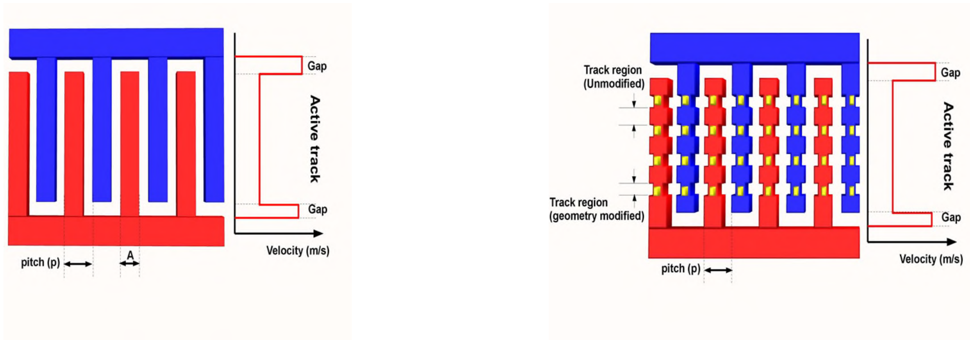
where $e(y)$ and $\psi^k(y)$ are the transversal excitation and mode profile of the k^{th} mode, respectively, and A is the aperture. Both functions, $e(y)$ and $\psi^k(y)$, are normalized. The higher modes are orthogonal to the fundamental mode. Therefore, the more excited the fundamental mode is, the more suppressed the higher modes are. Consequently, the fundamental mode dominates the conductance characteristics over the entire frequency range above the resonance frequency and no transversal modes will be visible or excited.

III. Expriment

In order to shape the favourable transversal mode profile with 2D periodic arrays, it is important to know the degrees of freedom for controlling it. Following our simulation, the variation of the velocity at the lower stopband edge is mainly relevant for mode profile shaping. The stopband width and the stopband center frequency individually are irrelevant. For an experimental proof of this concept, we investigated what we call the "Compensation effect".

A. *Compensation effect*

Here, "Compensation effect" is meant to be that transversal waves see no barriers along the transversal direction if the region with geometry modulation has the same effective velocity as the unmodulated track region. In Fig. 3, the structure without geometry variations (Fig. 3a), which serves as a reference structure, and the structure with geometry modulations (Fig. 3b), where the effective velocity is the same of the reference structure, are depicted respectively.
As to achieve the same velocities in both the modified and unmodified regions in Fig. 3b, the metallization ratio ($\eta = a/p$, where a is the finger width and p is the pitch of the fingers) in the unmodified region was varied keeping η in the modified region fixed, which is the area with the metal patch (Fig. 3b). In Fig. 4, the experimental results are plotted. Indeed, when both regions have the same effective velocity (or the same resonance frequency), the frequency characteristic of the



(a) Reference structure

(b) An equivalent structure

Fig. 3. Scheme of the geometry for the compensation effect and its $\Delta v/v$ waveguide profile.

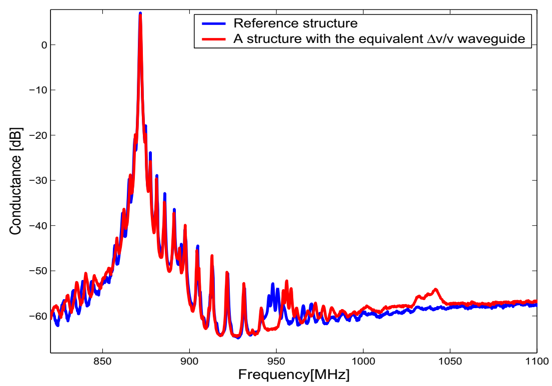


Fig. 4. Measurement of the frequency characteristic for the reference structure (blue) and a structure with the equivalent $\Delta v/v$ waveguide (red).

structure with geometry modification becomes very similar to the characteristic of the reference structure, i.e., the effect caused by the patches disappears. It suggests that the well for acoustic waves is formed by the effective velocity difference of two adjacent regions rather than by objects or the geometry itself.

Note that the frequency of the upper stopband edge for the equivalent case (around 960MHz) is higher than for the reference structure (Fig. 4). The reason is that the structure has higher reflectivity than the reference owing to the additional metal patches on the top of electrodes although the two different resonators have the same resonance frequency. Their mass loading and reflectivity are not identical but the effects are traded off each other and, consequently, it results in the same resonance frequency.

In addition, small peaks are also observable around 1040MHz for the equivalent case in Fig. 4 (red). Those are the transversal resonances being caused by the transversal periodicity. Since the reflectivity is dependent on the frequency, the effective velocity may not be the same at the high frequency range. Therefore the waves may see the periodic well in that regime.

B. Optimized periodic arrays with geometry variations

As to achieve the full suppression of the unwanted transversal modes using periodic arrays on the SiO_2-covered $LiNbO_3$ resonator, which possesses the favourable transversal mode profiles as described in Sec. II, it is very important that the arrays have the homogeneous periodic condition over the entire aperture. Using the above-mentioned 2D P-matrix tool, the required COM (coupling of modes) parameters and periodic $\boldsymbol{\Delta v/v}$ waveguide parameters in the modified and unmodified region were optimized for desired 2D behavior. On this basis, the fine-tuned real geometries were determined and the corresponding $\Delta v/v$ waveguide profile is shown in Fig. 5. We entitle the periodic waveguides by the periodic array as ”Periodic Velocity Wells (PVWs).

In the qualitative analysis of such a resonator with PVWs, we introduce a novel approach, which is analogous to a multiple quantum wells (MQWs) in solid state physics. In this approach, we initially consider that the PVWs form an infinitive cascade of single velocity wells, where each velocity well has translational symmetry according to Bloch's theorem, i.e.,

$$\psi_k(y) = u_k(y) \cdot e^{i\mathbf{k_{p_T}} \cdot \mathbf{y}}, \qquad (2)$$

where $\psi_{\mathbf{k}}(\mathbf{y})$ is the Bloch function, u_k is the wave function of a single velocity well, and k_{p_T} is $2\pi/p_T$ [7].

Similar to the energy level in a quantum well, we calculate the velocity of the first symmetric mode in a single velocity well with respect to the effective velocity ($v_m = \lambda \cdot f_m$), where f_m is the nth mode frequency and can be computed using a parabolic approximation of the slowness curve [1]. In reality, the number of PVWs is finite so that the perturbation of the first mode velocity increases toward the end of the PVWs. Therefore, throughout the optimization of the periodic arrays, the full periodic condition is achieved, i.e., the same velocity of the first mode in each well (Fig. 5 blue).

It is interesting to note that there is no interaction between the PVWs since they are not coulomb potentials so that no miniband is presented.

On the other hand, the complicated waveguide profile in the active track region can be simply treated like Fig. 3b

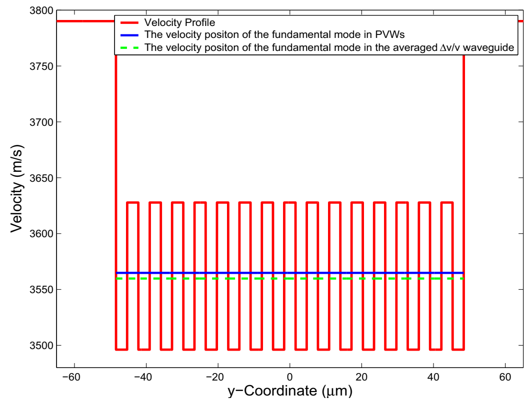


Fig. 5. Full periodic condition over the entire aperture. By the optimization of the periodic array, the velocities of the fundamental modes are aligned. Note that it is a simplified schematic of the $\Delta v/v$ waveguide. The plotted velocity profile is on the basis of the measured data.

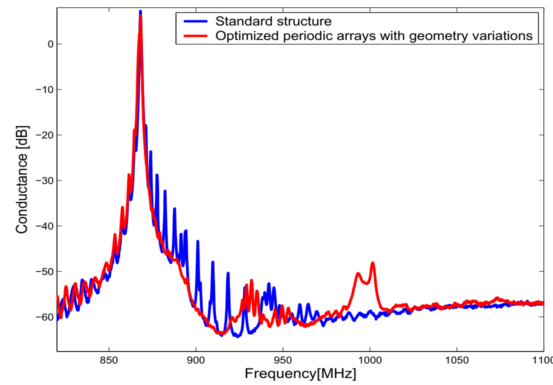


Fig. 6. Comparison of the mode suppression: a reference resonator (blue) and a resonator with the optimized periodic array (red). Measured data are plotted. The curve of the resonator with the periodic array is shifted to the resonance frequency of the reference resonator for ease of comparison.

since the resonator displays the resonance frequency at the averaged metallization ratio in the transversal direction. Thus, we are capable to calculate the transversal mode velocities for the averaged $\Delta v/v$ waveguide. In Fig. 5 (green dotted), the velocity of the first symmetric mode is indicated.

Theoretically, in order to maximize the excitation strength of the fundamental mode of the resonator, its velocity must be at the same level with the one from the optimized PVWs. In the presented case (Fig. 5), the mode velocities are slightly mismatched. It may be owing to the deviation of the measured real geometries. Since the optimization of the periodic arrays was carried out, the difference is minimized and the excitation strength of the fundamental mode is maximized. Furthermore, thanks to the orthogonality of each mode, the excitation strengths of the higher transversal modes are automatically reduced. In other words, since the velocities of the transversal modes lie in the PVWs' velocity region, the favourable transversal modes are automatically achieved (Fig. 2).

Thereby, we have achieved the full suppression of the unwanted transversal modes as well as the good suppression of the strong conductance by the transversal resonance. Fig. 6 shows the measurement of the resonator with the optimized 2D periodic arrays with geometry variations in comparison with the standard resonator which has no countermeasures.

IV. Conclusion and Discussion

Throughout this work, we have demonstrated that the variation of the velocity at the lower stopband edge is mainly relevant for mode profile shaping, and also that the stopband width and the stopband center frequency individually are irrelevant. Using this finding, the parameters for the periodic geometry variation were optimized. Besides, we have introduced a novel approach to explain the principle of the mode suppression in a resonator employing PVWs, where the approach is analogous to a multiple quantum well structure in solid state physics. It has successfully explained the principle of mode maximization and suppression.

Indeed, a resonator employing the optimized periodic arrays is capable to fully suppress all unwanted transversal modes within a certain bandwidth. In addition, the strong peak being caused by the transversal resonance is minimized, which is a prerequisite for the application in SAW filters. Therefore the optimized 2D periodic arrays on the electrodes can be readily employed for the design of SAW filters in SiO_2-covered $LiNbO_3$ with excellent performance.

There are still two remaining questions: i) the effect of the PVWs height and ii) correlation between the transversal acoustic band gap and the periodic array. It may be in a way analogous to wave propagating effects in multiple quantum wells. Currently, we are on further investigation in order to explain it more clearly.

Acknowledgment

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