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Modeling of a high frequency ultrasonic transducer using periodic structures

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Abstract

Solidly mounted integrated transducers with a Bragg cell inserted between the piezoelectric film and the substrate are investigated for high frequency ultrasonic applications. A numerically stable recursive one dimensional transmission/reflection model was used to analyze the behavior of the periodic structure. This theoretical analysis includes the study of the influence of the acoustic properties of the constitutive layer, the effect of the number of cells and their arrangement. A 35 MHz integrated transducer consisting in a PZT ceramic laid down on a Au/PZT Bragg cell deposited on a porous substrate was fabricated and characterized. Both theoretical and experimental results highlight the interest of using a periodic structure for high frequency ultrasonic applications.

Keywords: Periodic structures; Piezoelectric transducer; High frequency

1. Introduction

The development of new fields of applications in imaging systems (>30 MHz) such as skin imaging, or small animal imaging requires enhanced ultrasonic imaging systems. As a consequence, new high resolution, high frequency ultrasonic transducers are being developed using various processing routes [1–5]. Indeed conventional techniques that consist in the assembly of a piezoelectric ceramic, a backing and one or several matching layers can no longer be used directly. The handling of the ceramic become critical at such frequencies, as well as the electrode or glue thicknesses. To overcome these difficulties, high frequency integrated transducer can be directly fabricated using the screen-printing of a piezoelectric ceramic on a solidly mounted backing [6–9], but this technique uprises technological difficulties. First of all, as the ceramic is directly laid down an electroded substrate and sinterred at temperature higher than 700 °C, the substrate needs to be compatible with such process. Polymer based backing, which are very often used, can no longer be employed in such transducers. Silicon, alumina or even metallic substrates can be used. Such substrates will lead to a damping of the resonance of the ceramic because of their high acoustic impedance, but will generate spurious echos in the electroacoustic response of the transducer because of their low attenuation. Recently, the use of porous substrate materials (porous PZT ceramic) has been demonstrated for high frequency transducer applications [9]. Here, the substrate plays its role of backing, but the acoustic impedance is typically between 20 and 25 MRa, relatively close to that of a piezoelectric ceramic and leads to a strongly damped piezoelectric resonance. As a result this may decrease the penetration depth in the tissues.

Here, we propose a concept of integrated transducer that consists in completely reflect the ultrasonic waves by the mean of a Bragg cell inserted between the piezoelectric layer and the substrate [10,11]. The modeling is based on a one dimensional approach. Numerous papers

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dealing with transmission in one dimensional passive multilayer structures, commonly based on the transfer matrix formulation, have been published [12–14]. Unfortunately, such a transfer matrix approach leads to numerical instabilities for a high number of layers in periodic configurations. An accurate and numerically stable recursive model is used as an alternative for its numerical stability [15,16]. First, the related formulas for the reflection and transmission coefficients are presented without restriction to periodicity. Then, the case of a Bragg cell on a substrate is presented as a way to modify the input impedance of the backing. Secondly, as the available material combinations are restricted by thermal and chemical compatibility, the ratio of acoustic impedance between the two layers constituting the Bragg cell is limited. The influence of the acoustic impedance ratio on the transmission coefficient is examined. Two compatible sets of materials (Au/PZT or Pt/Al_2O_3) are discussed. The influence of the number of layers is discussed both in terms of minimum value and bandwidth. Then, the high frequency transducer design is presented, using a recursive calculation of the input impedance of the backing. Finally, experimental results are presented for a Bragg cell made of Au/PZT.

2. Modeling

The modeling of a periodic structure is developed on the basis of a one dimensional assumption. It takes into account multiple reflections between the interfaces. This modeling can be performed using the transfer matrix formalism [12–14], but this can lead to numerical instabilities due to the bad matrix conditioning. A recursive approach giving accurate results for any type of configuration is preferred [15,16].

Using the notation proposed by Conoir [16], the Fresnel reflection and transmission coefficients, R and T, at the interface between layers indexed n and $n+1$ are:

$$R_{n,n+1} = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n} \mathrm{e}^{+2j\varphi_n}, \tag{1}$$

$$\text{and } T_{n,n+1} = \frac{2Z_{n+1}}{Z_{n+1} + Z_n} \mathrm{e}^{-j(\varphi_{n+1} - \varphi_n)} \tag{2}$$

Reciprocally, between layer n+1 and layer n:

$$R_{n+1,n} = \frac{Z_n - Z_{n+1}}{Z_n + Z_{n+1}} \mathrm{e}^{-2j\varphi_{n+1}}, \tag{3}$$

$$\text{and } T_{n+1,n} = \frac{2Z_n}{Z_n + Z_{n+1}} \mathrm{e}^{-j(\varphi_{n+1} - \varphi_n)}, \tag{4}$$

where Z_n is the acoustic impedance, $\varphi_n = k_n z_n = \omega z_n / c_n$ and $\varphi_{n+1} = k_{n+1} z_n = \omega z_n / c_{n+1}$ are the phases expressed as a function of the interface position z_n, wave number k_n, with angular pulsation ω and longitudinal wave velocity c_n.

The reflection coefficient of a multilayer structure having N layers is calculated from layer $n = N$ to layer 1:

$$\begin{gathered} R = R_{12} + \frac{T_{12}\rho_{23}T_{21}}{1 - R_{21}\rho_{23}}, \\ \text{where } \rho_{n,n+1} = R_{n,n+1} + \frac{T_{n,n+1}\rho_{n+1,n+2}T_{n+1,n}}{1 - R_{n+1,n}\rho_{n+1,n+2}}, \\ \text{for } 2 \leqslant n \leqslant N \text{ and } \rho_{N+1,N+2} = R_{N+1,N+2}. \end{gathered} \tag{5}$$

The transmission coefficient of a multilayer structure is calculated similarly from layer $n = 1$ to layer N:

$$\begin{gathered} T = T_{12} \prod_{n=2}^{n=N} \frac{T_{n,n+1}}{1 - R_{n,n+1}\rho_{n,n-1}}, \\ \text{where } \rho_{n+1,n} = R_{n+1,n} + \frac{T_{n+1,n}\rho_{n,n-1}T_{n,n+1}}{1 - R_{n,n+1}\rho_{n,n-1}}, \\ \text{for } 2 \leqslant n \leqslant N \text{ and } 1\ \rho_{21} = R_{21}. \end{gathered} \tag{6}$$

This formalism is then used to model periodic structures (Fig. 1) for high frequency transducer applications. Acoustic attenuation could be taken into account using this model when considering a complex wave number. Nevertheless, its effect would not be significant within the context of this study since the main wave propagation paths do not exceed a few wavelengths.

Throughout the study, the layers constituting the periodic structure will be considered lossless and quarter wavelength thick.

3. Influence of the constitutive layers

3.1. Acoustic impedance ratio

The transmission coefficient of an elementary stack is calculated for various acoustic impedance ratios as a function of normalized frequency (Fig. 2a). The higher the acoustic impedance mismatch, the lower is the transmission coefficient. Fig. 2b shows the evolution from 0 (total reflection) up to 1 (total transmission) as a function of the acoustic impedance ratio. Vertical lines indicate two sets of materials, i.e. Au/PZT and Pt/Al_2O_3, compatible with thick film technology, the properties of which are listed in Table 1.

3.2. Number of stacks

For the two selected sets of materials, an increase of the number of elementary stacks N_s induces a stop-band in the

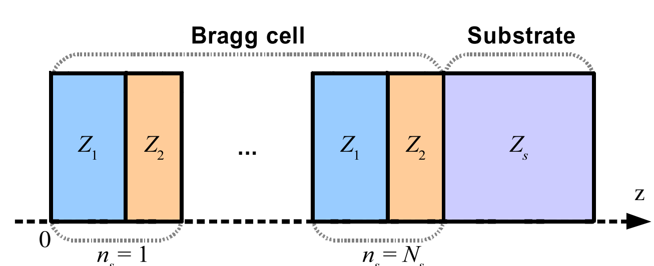

Fig. 1. Periodic structure made of N_s elementary stacks of $N_{layers} = 2$ layers deposited on a substrate.