Solidly-Mounted Agile Resonator / Transducer

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***Abstract* - Solidly mounted resonators (SMRs) were proposed by Newell in the mid-1960s. Decoupling from the mounting substrate was achieved at a single frequency by a Bragg stack of quarter-wavelength plates. While the initial concept was ahead of fabrication technology, SMRs are now a practical resonator design yielding high Qs in a space-efficient and robust mounting configuration. This paper introduces the concept of a Bragg anti-reflection stack made adjustable by endowing each layer with piezoelectricity and providing for changing the electrical boundary conditions.**

I. Introduction

The face-mounted resonator was described by Newell in 1964 [1-3]. It consisted of a piezo-active resonator surmounting a stack of quarter-wavelength layers of alternating acoustic impedance, bonded to a robust substrate. This configuration afforded a solid mounting support, a miniaturizable geometry, and, most importantly, a mechanical impedance at the resonator mounting surface approximating a short-circuit, so that high resonator quality factor (Q) values could be maintained. Despite some encouraging preliminary experimental results, including discovery of enhanced unwanted mode suppression, the concept proved to be ahead of necessary microfabrication technologies. More recently, advances in fabrication modalities have been used to fashion modern realizations of the face-mounted resonator, now called the solidly-mounted resonator (SMR) [4-23].

To date, acoustic stack plates in SMRs have been utilized only for their mechanical properties as impedance transformers. Use of stacks containing a piezoelectric layer or layers provides an additional degree of freedom, because the electrical boundary condition on the piezoelectric layer or layers may be altered. This adjustment may be done as a fixed tuning measure, or actively, to vary or modulate the stack properties seen by the resonator or transducer. Figure 1 depicts schematically an agile SMR, where adaptive circuitry dynamically alters the tuning of the Bragg stack.

II. Discussion

The stack of layers performs in a manner similar to a Bragg antireflective coating used on camera lenses. In the optical case the stack consists of alternating layers having high and low indices of refraction. In the usual acoustic case, the stack consists of alternating layers of material of high and low acoustic impedance. Having alternating layers is not enough, however. The necessary condition is that, at the frequency of interest, each layer be approximately ¼ of an acoustic wavelength thick. The layers can each be considered an acoustic transmission line (TL). It is a property of a TL to transform any impedance attached to one end, so that when looking into the other TL end, one sees a different impedance. If an impedance Z_T (T = "termination") is attached to one end of a TL having a characteristic impedance Z_o, then looking into the other end of the TL one sees an input impedance given by the expression:
$Z_{input} = Z_o [Z_T + j Z_o \tan(\theta)]/[Z_o + j Z_T \tan(\theta)]$; $\theta = (2\pi f \ell)/v$, where "f" is the operating frequency (usually a variable quantity), "ℓ" is the geometrical thickness of the layer, and "v" is the acoustic velocity in the layer; wavelength is $\lambda = v/f$.

When the TL is of negligible length, ℓ is approximately zero, so θ and tan(θ) are about zero. In this case, Z_{input} is about Z_T, as one would expect. On the other hand, if frequency is such that ℓ is approximately λ/4, then θ will be about π/2, tan(θ) will be very large, and the two tangents will cancel out, leaving Z_{input} about equal to Z_o^2/Z_T. Thus, in the vicinity of this particular frequency, the input impedance will be changed from Z_T to Z_o^2/Z_T. The transformation that takes place when the stack consists of alternating layers of high (Z_H) and low (Z_L) impedance values, and each is about λ/4 thick, results in an input mechanical impedance at the face of the resonator of approximately $[Z_L (Z_L/Z_H)^N]$, where N is the number of pairs of layers.

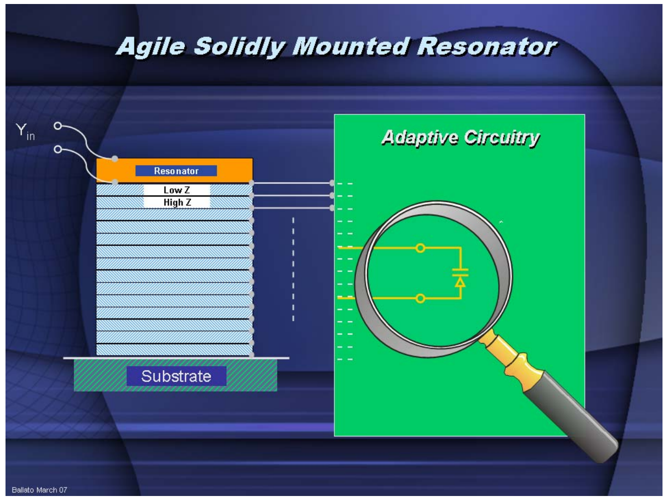

Figure 1. Piezoelectric SMR attached to control circuitry.

This means that the bonded face of the resonator "sees" an acoustic impedance that is very low. A low value of acoustic impedance (approximating a mechanical short circuit), means that the resonator face is traction-free, and decoupled from the layers and substrate. The resonator is unable to radiate any acoustic power down the stack and into the substrate; virtually all is reflected back into the resonator, so the Q remains undiminished. The only source of loss is the loss within the resonator itself; for low acoustic loss materials, this is quite small, and high Q values can be realized.

To this point, nothing is new. The new feature is the word "agile" in the title. In the TL discussion above, words such as "about" and "approximately" were used. This is for a number of reasons, among

which are: 1) Manufacturing considerations make it infeasible to make all layers exactly the same acoustic length; there will always be some fabrication deviations from the ideal, leading to suboptimal performance. The electric ports of the piezo Bragg mirror strata can be used to correct for these deviations. Newell [2] made an analysis of the effect of manufacturing devaitions; this consideration is also found in [7].
2) Devices using resonators, such as filters, operate over a range of frequencies. If the stack layers are $\lambda/4$ thick at one frequency, they can't be at any other frequency, since $\lambda = v/f$. As frequency changes, so does λ.

Reference [7] contains computer simulations of the behavior of SMRs under various conditions. Their Fig. 4 shows the behavior of input admittance at the electrical port of the resonator when the stack layers are made to be $\lambda/4$ thick at the *antiresonance* frequency of the resonator. In this case, the responses for different numbers of bilayers in the stack line up, and have minima at the same frequency, that of the resonator *antiresonance*. It is also seen that the maxima for various numbers of bilayers do not align with the maximum for the resonator alone (i.e., the traction-free case). In their Fig. 5 is shown the behavior of input admittance at the electrical port of the resonator when the stack layers are made to be $\lambda/4$ thick at the *resonance* frequency of the resonator. In this case, all the responses for different numbers of bilayers in the stack line up, and have maxima at the same frequency, that of the resonator *resonance*. It is also seen that the minima for various numbers of bilayers do not align with the minimum for the resonator alone.

Piezoelectric strata afford the possibility of loading the electrical ports to change properties, and thereby to change the characteristics of the SMR. Lawson [24] alluded to this phenomenon, because at the resonance frequency the apparent TL length L', due to piezoelectricity, exceeds the geometrical length L. For small coupling, the relation is $L' \approx L/[1 - (2k/\pi)^2]$.

One simple method of operation is to alternate between an open circuit (OC) condition, and a short circuit (SC) condition. Since the SMR can be mounted contiguous to an integrated circuit, or even be an integral part of one, it is quite easy to have a great many transistors, diodes, and capacitors available to do whatever switching and adjusting functions as may be necessary.

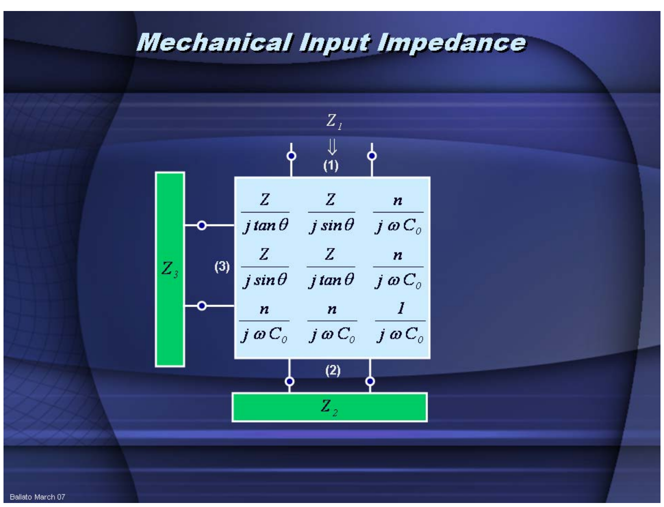

Figure 2. Mechanical input impedance of piezo layer with electrical and mechanical port loadings.

III. Mechanical Input Impedance

A piezoelectric plate, with one mechanical port attached to a load Z_2, and the electrical port attached to a load Z_3, as in Fig. 2, has a normalized mechanical input impedance seen at port (1) of $(Z_1/Z) = [A - k^2 B]/[C - k^2 D]$, where $A = [Z_2 + j\,Z \tan(\theta)] \cdot (1 + j\,Z_e)$; $B = [Z_2\,T(\theta) + j\,Z \tan(\theta)\,T(\theta/2)]$; $C = [Z + jZ_2 \tan(\theta)] \cdot (1 + j\,Z_e)$; and $D = [Z\;T(\theta)]$, where $Z_e = [Z_3\,(\omega C_o)]$, and $T(x) = [\tan(x)/x]$. For a variable capacitor on port (3), $Z_3 = 1/(j\omega C_o\zeta)$; $\zeta = 0$: open circuit; $1/\zeta \rightarrow 0$: short circuit. Figure 3 gives relations for (Z_1/Z) under OC and SC conditions. For non-piezoelectric stacks ($k^2 = 0$), the OC equation for a loaded transmission line (TL) is used recursively to transform from layer to layer; in the piezoelectric case, it is necessary to use the more general relation given above. In the limit of $Z_2 = 0$ (free surface),
$(Z_1/Z) = j\tan(\theta) \cdot \{[1 - k^2\,T(\theta/2)] + j\,[Z_e]\}/\{[1 - k^2\,T(\theta)] + j\,[Z_e]\}$,
and when $1/Z_2 \rightarrow 0$ (rigid surface),
$(Z_1/Z) \rightarrow [1/(j\tan(\theta))]\{[1 - k^2\,T(\theta)] + j\,[Z_e]\}/\{1 + j\,[Z_e]\}$.

IV. Electrical Input Impedance

A piezoelectric plate, with mechanical ports attached to loads Z_1 and Z_2, as in Fig. 4, has a normalized electrical input impedance seen at port (3) of $[Z_3\,(j\omega C_o)] = z_{in} = [1 - k^2\{[N_1 + jN_2]/[D_1 + jD_2]\}]$, where $N_1 = [Z(Z_1+Z_2)T(\theta)]$; $N_2 = [Z^2 \tan(\theta)T(\theta/2)]$; $D_1 = [Z\,(Z_1+Z_2)]$; and $D_2 = [(Z^2 + Z_1Z_2)\tan(\theta)]$. Figure 5 gives the relation when one surface is free ($Z_1 = 0$). In the limit where one surface is free and the other is clamped $1/Z_2 \rightarrow 0$, $z_{in} = [1 - k^2 T(\theta)]$; if both surfaces are clamped, $z_{in} = 1$, and if both surfaces are free, $z_{in} = [1 - k^2 T(\theta/2)]$. In Figs. 2 and 4, the piezoelectric transformer ratio, n, is related to the other parameters by $n^2 = [Zk^2\omega C_o/\theta]$.

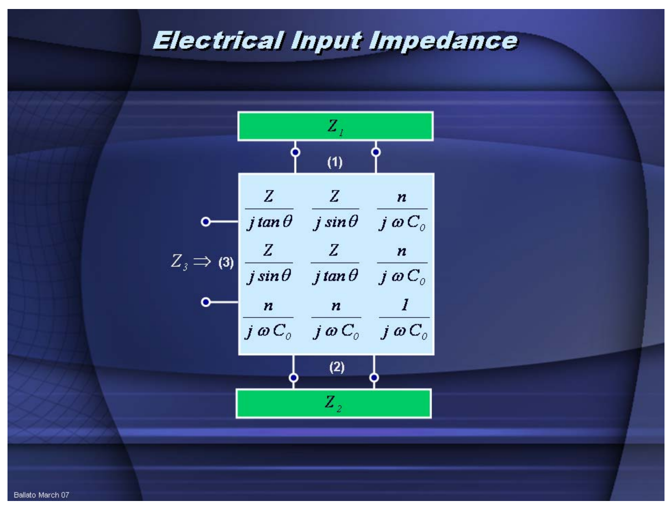

Figure 4. Electrical input impedance of piezo layer with loads on both mechanical ports.

V. Piezoelectric Stacks

Definitions: $Z_{substrate} = \{[0,0,0], [0,Z,0], [0,0,0]\}$; $Z_H = \{[Z_{11H}, Z_{12H}, Z_{13H}], [Z_{12H}, Z_{11H}, Z_{13H}], [Z_{13H}, Z_{13H}, Z_{33H}]\}$; $Z_L = \{[Z_{11L}, Z_{12L}, Z_{13L}], [Z_{12L}, Z_{11L}, Z_{13L}], [Z_{13L}, Z_{13L}, Z_{33L}]\}$; Z_{Hk} layer $= \{[0,0,0], [0,Z_{2Hk},0], [0, 0,Z_{eHk}]\}$; Z_{Lk} layer $= \{[0,0,0], [0,Z_{2Lk},0], [0,0,Z_{eLk}]\}$; $Z_{L1} = \{[0,0,0], [0,Z_{2L1},0], [0,0,0]\}$; $Z_{resonator} = \{[Z_{11}, Z_{12}, Z_{13}], [Z_{12}, Z_{11}, Z_{13}], [Z_{13}, Z_{13}, Z_{33}]\}$.

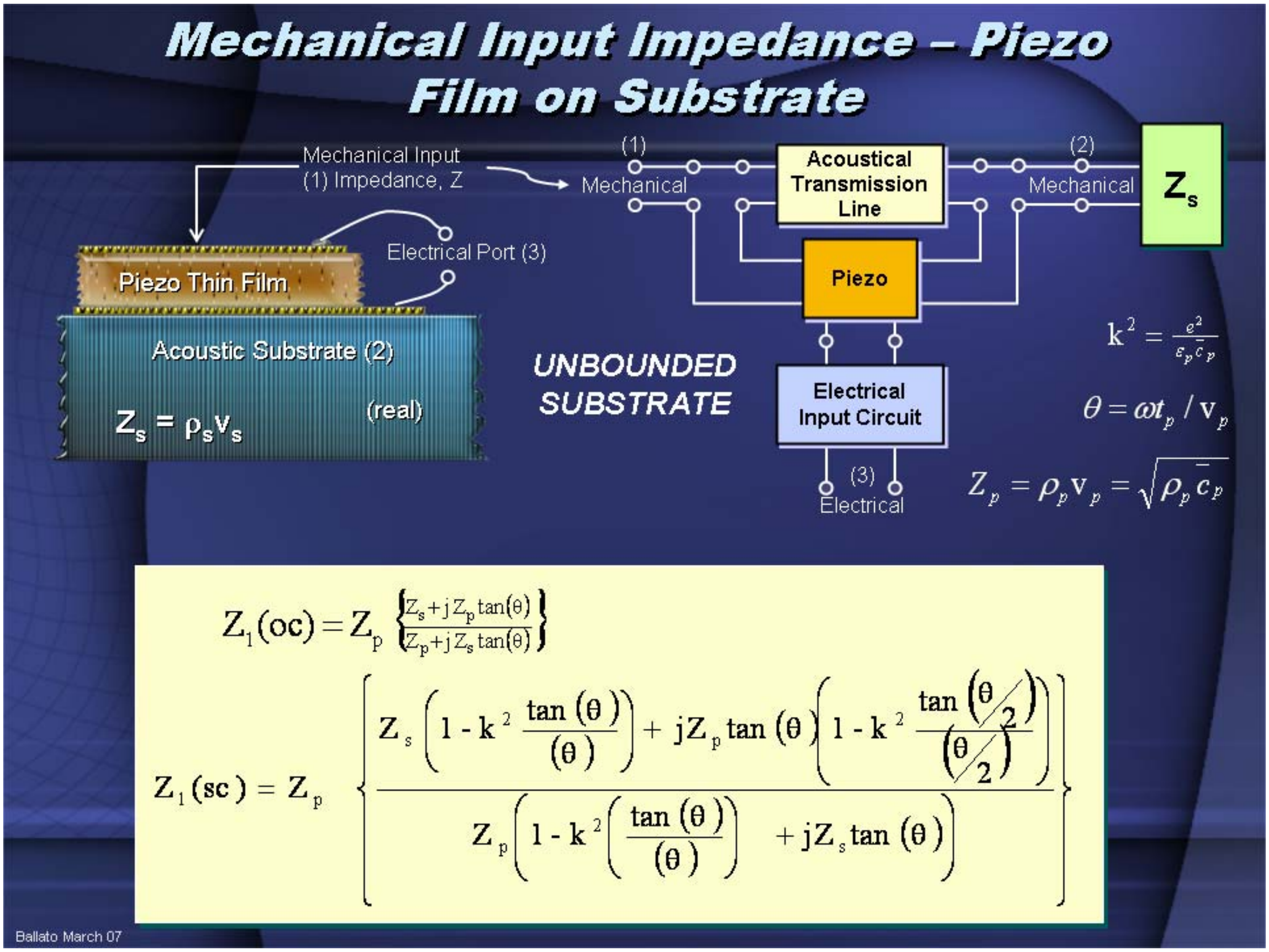

Figure 3. Mechanical input impedance for structure of Fig. 2 with open- and short-circuit electrical boundary conditions.

Recursive relations for a piezo-Bragg stack of k bi-layers then are: $W_{Hk} = Z_H+Z_{substrate}$; $Y_{Hk} = ((W_{Hk})^{-1})_{11}$; $Z_{1Hk} = (Y_{Hk})^{-1} = Z_{2Lk}$ (into Z_{Lk}); $W_{Lk} = Z_L+Z_{Lk}$; $Y_{Lk} = ((W_{Lk})^{-1})_{11}$; $Z_{1Lk} = (Y_{Lk})^{-1} = Z_{2H(k-1)}$ (into $Z_{H(k-1)}$); $W_{H(k-1)} = Z_H+Z_{H(k-1)}$; $Y_{H(k-1)} = ((W_{H(k-1)})^{-1})_{11}$; $Z_{1H(k-1)} = (Y_{H(k-1)})^{-1} = Z_{2L(k-1)}$ (into $Z_{L(k-1)}$); et seq., and finally the resonator input impedance Z_{in} is found from: $W_{resonator} = Z_{resonator}+Z_{L1}$; $Y_{resonator} = ((W_{resonator})^{-1})_{33}$; $Z_{in} = (Y_{resonator})^{-1}$.

VI. Simulations

To minimize the number of variables, the following simplifications have been employed: No electrode mass/thickness; no losses (except radiation into unbounded substrate); unit area; all electrical port loadings equal and normalized to a fraction of the impedance of C_o: $Z_{3H} = Z_{3L} = 1/(\zeta\ j2\pi f_A C_o)$; $Z_L = mZ$, and $Z_H = Z/m$, (Z = mechanical impedance of resonator and substrate); acoustic velocities and thicknesses equal: $v_H = v_L = v = v_{resonator} = v_{substrate}$; $t_H = t_L = t$, so $\theta_H = \theta_L = \theta = \omega t/v$; resonator thickness $\ell = 2t$; $\theta_{resonator} = 2\theta$; piezocouplings: $k_H = k_L$.

Figure 6 shows plots of a ten-bilayer SMR stack at OC and SC conditions, along with that of a free-free resonator. The stack may be tuned from the resonance to the antiresonance resonator frequencies.

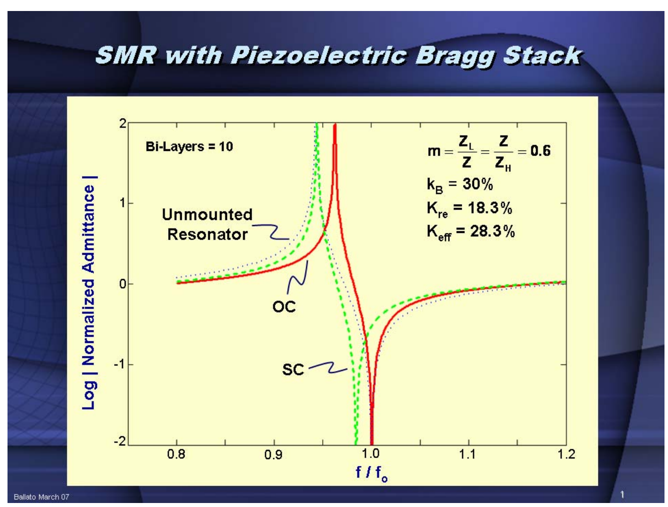

Figure 6. Ten bi-layer SMR Bragg stack with open-circuit anti-resonance frequency adjusted to coincide with that of the free resonator, and the short-circuit resonance frequency adjusted to coincide with free-resonator resonance frequency.

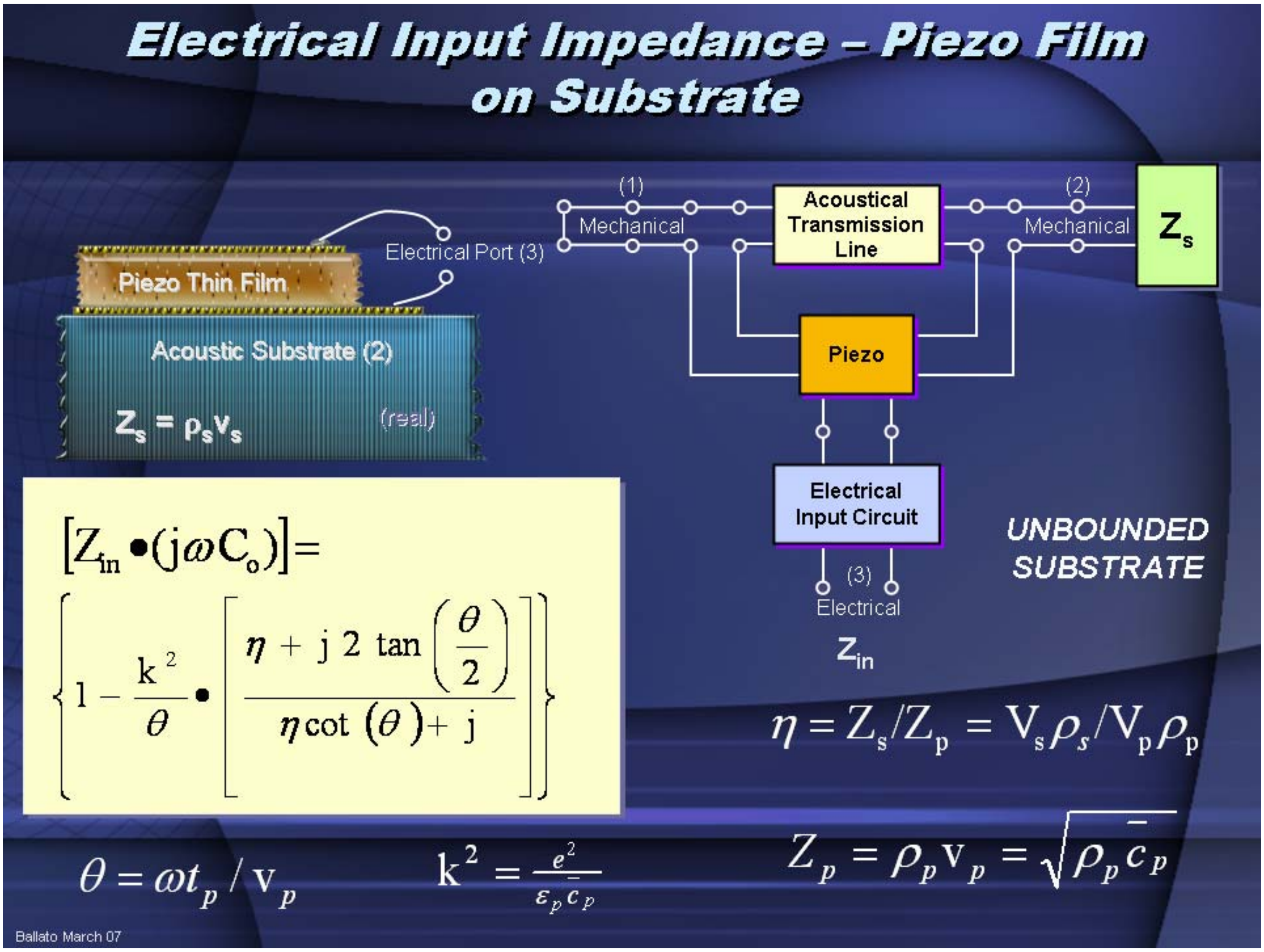

Figure 5. Electrical input impedance for structure of Fig. 4, but with one mechanical load short-circuited (free surface).

TABLE I. RELATIVE POWER INTO SUBSTRATE

Normalized Frequency, Ω	Re (Y_{in}) (SC)	Re (Y_{in}) (OC)
$0.809 \approx \Omega_g$	0.0152	0.0371
0.837	0.0150	0.0351
0.866	5.14E-3	0.0114
0.894	1.80E-3	4.00E-3
0.922	9.37E-4	2.14E-3
0.951	1.28E-4	2.38E-4
$0.9635 \approx \Omega_R$	1.61E-4	4.31E-4
0.980	8.90E-7	3.30E-6
1.008	1.74E-8	4.83E-8
$1.0365 \approx \Omega_A$	2.36E-5	7.02E-5
1.037	2.41E-5	7.16E-5
1.065	3.45E-4	1.01E-3
1.094	1.29E-3	3.87E-3
1.122	3.35E-3	0.0104
1.151	9.80E-3	0.0298
1.179	0.0280	0.0817
$1.208 \approx \Omega_h$	0.0317	0.0905

VII. POWER INTO SUBSTRATE

A source immittance will appear in the expression for power delivered to the substrate, but for a pure voltage source (SC), power = ½ $V^2G \propto$ Re[Y], and for a pure current source (OC), power = ½ $I^2R \propto$ Re[Z]. Table 1 gives the Q-degrading relative power lost into the substrate at SC and OC conditions, between the normalized equi-immittance frequencies, where $\Omega_{h,\,g} = 1 \pm (2k/\pi)$.

VIII. CONCLUSIONS

♦ Use of a piezoelectrically adjustable Bragg stack provides an added degree of freedom, allowing:
– Compensation for manufacturing deviations in each layer
– Dynamic programming, to keep Bragg stack tuned to input frequencies
– High Q over filter bandwidth
♦ Adjustment takes place by varying immittance load on one, some, or all plates in the Bragg stack (passive adjustment)
♦ Application of time-varying signal sources is enabled (active adjustment or compensation)

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