AN INNOVATIVE PIEZO-MEMS CHANNEL-SELECT FILTER DESIGN BASED ON NON-MONOTONIC COUPLED MODES

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ABSTRACT

We propose a novel mechanically-coupled filter design which *for the first time* combines two distinct physical vibration modes, including length-extensional (LE) and degenerate in-plane shear (IPS) modes excited in a single filter structure, fabricated using InvenSense AlN-on-silicon platform. By taking advantage of typical LE-based (LE-LE) and IPS-based (IPS-IPS) monotonic filter designs but without their inherent constraints, the proposed non-monotonic coupled mode (IPS-LE) filter simultaneously features a nodal-point positioned filter coupler and a differential operation, hence enabling narrow-band filtering and significant feedthrough reduction toward channel-select applications. Notably, the proposed filter topology is also capable of addressing the fly-back issue observed from IPS-based filter. As a result, the designed 34.8-MHz piezo-MEMS filter is successfully demonstrated with a flat passband, 0.18%-bandwidth (63 kHz), and 30-dB stopband rejection under proper termination resistances (R_Q).

INTRODUCTION

Toward the smart living, the machine to machine communication (M2M) technology attracts significant attention for developing the emerging Internet of Things (IoT) systems that benefit transportation, energy grids, and healthcare. For instance, in order to enable the multiple-functionality sensor nodes for healthcare or self-monitoring of chronic disease [1], the body area networks (BANs) are employed for real-time diagnostic and medical monitoring purposes for which the smartphone or telehealth hubs can collect the data from several active implantable medical devices (AIMDs), as shown in Fig. 1. For the data transmissions, a new standard referred to as medical body area network (MBAN) and medical implant communications service (MICS) are widely used for the low power network of sensors worn on human bodies.

Therefore, the wireless body area network (WBAN) [2] should feature low output power (i.e., several tens to hundreds μW) with very short distance communication (around 1-2m). In addition to the power-saving characteristic, it also needs to eliminate the power handling issue of filters in RF or IF front-ends. Regarding the signal receiving, the multiple-band operation is actively pursued for receiving the vital signs from different sensors mounted on or closed to the human body. To reduce the interference from adjacent channels, the channel-select (i.e., narrow band) specification is necessitated for a low-cost and multiple-functionality front-end. To satisfy the requirement of the abovementioned applications, MEMS resonant filters based on piezoelectric transduction [3][4] have recently become an attractive solution for power-saving signal processing and sensing systems. Although the capacitive counterparts [5][6] take advantage of small form factor and high quality factor (i.e., small percent bandwidth), the most capacitive filters still suffer from the limited transduction efficiency and insufficient power handling, thus barricading the practical use in wireless sensor nodes communication. On the other hand, owing to the benefit from excellent electro-mechanical

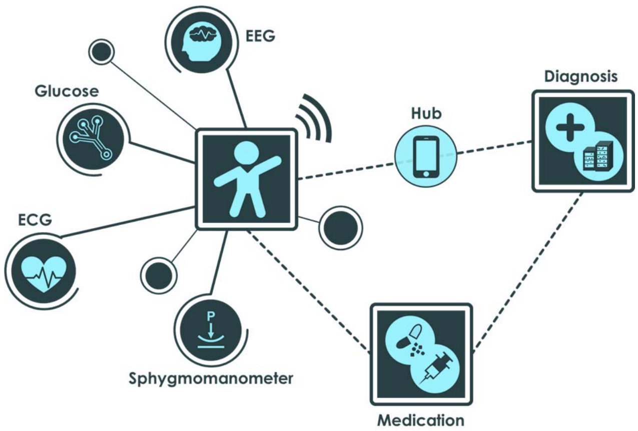

Figure 1: MEMS-enabled WBAN for connectivity demand on wearable, implantable, and IoT applications.

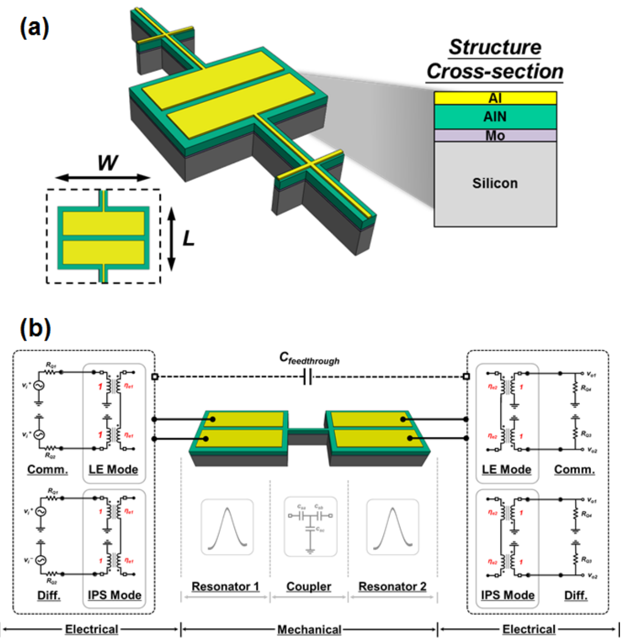

Figure 2: (a) The conceptual plot for basic resonant tank with a two-port configuration, showing the structure stacking employed in this work. (b) Schematic description of mechanically-coupled piezo-MEMS filters, indicating their corresponding electromechanical transformation for the LE-based, IPS-based, and proposed non-monotonic mode coupled filter configurations.

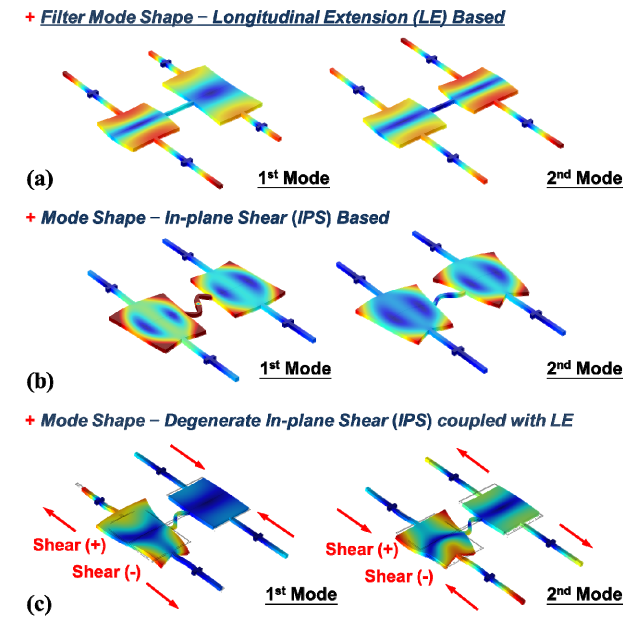

Figure 3: Filter mode shapes of (a) the LE-based filter, (b) the IPS-based filter, and (c) the proposed IPS-LE coupled filter for which the filter coupler is positioned at the nodal point of the output resonator (i.e., LE mode) to enable a narrow bandwidth characteristic.

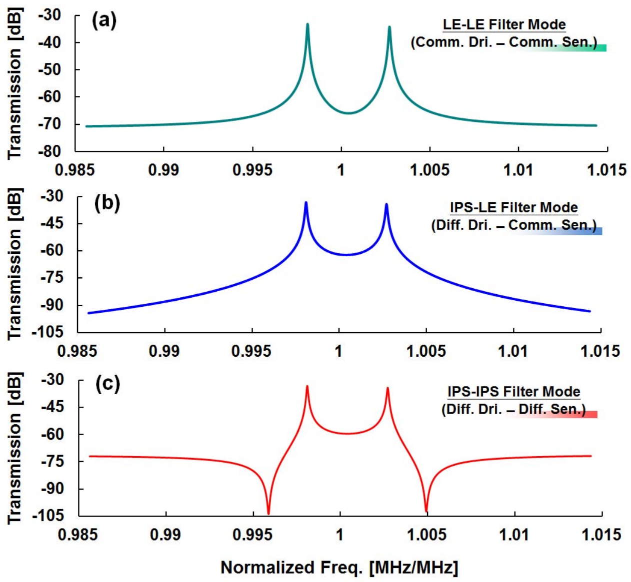

Figure 4: Simulated frequency characteristics resulted from a filter equivalent circuit under (a) LE-LE, (b) IPS-LE, and (c) IPS-IPS filter configurations, indicated in Fig. 2(b).

coupling coefficient (η_e), the piezoelectric devices are capable of attaining low insertion loss and decent signal-to-noise ratio (SNR) with wide frequency operation capability (e.g., in MHz to GHz range) for front-end applications.

In this work, the InvenSense AlN-on-Silicon platform [7] is adopted for very high frequency (VHF) piezoelectric bandpass filter implementation. To perform the filter response, two adjacent rectangular plates with a two-port configuration are physically linked by a slender coupler to create a well-defined bandwidth. Additionally, a non-monotonic coupled mode filter for the first time was proposed where two distinct resonant modes are combined in a single filter structure with differential operation to simultaneously enable a narrow bandwidth and satisfactory stopband rejection performance, thus paving a way for MEMS-based multi-channel signal processer in future wearable/IoT electronics.

TRANSDUCER / FILTER DESIGN

Among the attractive solution provided by piezo-MEMS technologies, the AlN-based resonator is used to prove our proposed scheme. To obtain low-loss characteristics, a rectangular AlN-on-silicon plate with a horizontal two-port configuration, as depicted in Fig. 2(a), is often adopted as a resonant tank for mechanically-coupled filters to maximize the transduction efficiency while the composite piezoelectric plate can be excited into multiple in-plane modes, such as length-extensional (LE) and in-plane shear (IPS) modes.

In particular, the *cross* anchoring design composed of two extensional, quarter-wavelength (λ/4), supporting beams [8] is used to create pseudo nodal points which not only suppress the possible anchor loss to keep decent quality factor but also reduce the design complexity as compared to a traditional T-shape support [9]. Fig. 2(a) exhibits the structure cross-section in InvenSense AlN-on-Silicon platform. Similar to the prior art reported in [10], the MEMS structure starts with the single crystal silicon, bottom electrode Mo, piezoelectric layer AlN, and top electrode Al to define the effective transduction region. Moreover, to implement a filtering building block with a desired bandwidth, a physical coupler with optimized geometry is employed to mechanically couple two adjacent resonant tanks as illustrated in Fig. 2(b). Note that the silicon substrate possesses a relatively high quality factor nature; hence the constituted AlN resonant tanks are able to create sufficient *Q*-factor performance [11], enabling a small fractional bandwidth toward the filtering application.

Fig. 2(b) illustrates the conceptual schematic of a mechanically-coupled filter, not only showing the corresponding transformation between electrical and mechanical domains, but also delineating the possible mode combination from constituted resonators in a single filter structure. Obviously, the LE-based filter, presented in Fig. 3(a), suffers from significant parasitics due to the limitation of its common-mode drive/sense operation. On the other hand, the IPS-based filter is the preferred topology for a satisfactory out-of-band rejection based on its mechanically-differential nature as depicted in Fig. 3(b); however, the filter coupler cannot be positioned at the nodal points of the constituent resonators to form a narrow bandwidth for channel selection [12]. To address abovementioned issues, the IPS-LE (non-monotonic) coupled filter is proposed in this work as shown in Fig. 3(c).

Fig. 4 presents simulation results based on an equivalent circuit model illustrated in Fig. 2 (b) (amplitude is normalized). As aforementioned, the considerable background feedthrough level caused by the input-to-output parasitic path ($C_{feedthrough}$) becomes problematic for LE-based filters. Although the IPS-based

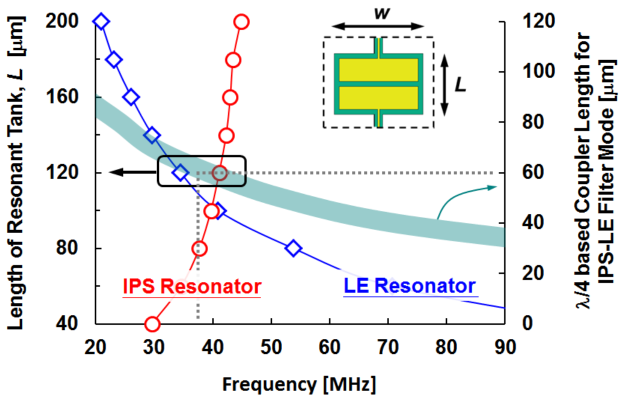

Figure 5: Design guideline of the proposed filter where the 90µm and 2µm widths are used for the resonant tank and filter coupler, respectively. The frequency of the specific coupler is suggested to design between the region of LE and IPS vibrations.

counterpart is capable of creating excellent filter shape factor using additional notches at the both sides of the filter passband through fully differential operation [13], the filter has to overcome the undesirable fly-backs in the practical implementation. This motivates the study utilizing non-monotonic coupled modes which gain both merits from the monotonic filters without their issues.

The proposed IPS-LE filter topology possesses two advantages as compared to conventional designs, including (i) an inherent differential operation on the drive resonator for feedthrough reduction (w.r.t. LE-based); (ii) a filter coupler positioned at the nodal point of the sense resonator to attain a narrower passband (w.r.t. IPS-based). To achieve the proposed filter, the design curves in Fig. 5 suggest: (i) the LE and IPS vibration frequencies should stay close enough to prevent the undesired spurious modes in between; (ii) the frequency of the λ/4-based IPS-LE coupler should lie in the region between LE and IPS modes, which would permit both modes coupled in a filter structure, hence forming narrow bandwidth. Eventually, the resonator and filter coupler lengths of 120 µm and 60 µm were selected to fulfill all the requirements of the proposed filter. Notably, the symmetric transduction area for constituent resonators can greatly relax the complexity of filter termination.

MEASUREMENT RESULTS

Fig. 6 presents the global SEM and OM views of a fabricated mechanically-coupled piezo-MEMS filter where a slender coupler fulfilling the λ/4-length for IPS-LE non-monotonic mode coupling is close to a low-velocity position for obtaining a narrow passband. To experimentally verify the capability of narrow passband characteristic and feedthrough cancellation by the non-monotonic coupled mode (i.e., IPS-LE) operation, Fig. 7 shows the comparison of measured frequency spectra among three different filter configurations, including (i) LE-to-LE, (ii) IPS-to-LE, and (iii) IPS-to-IPS coupled modes, where the numbers (from 1 to 4) of S-parameter represent different ports as depicted in Fig. 2. Apparently, due to the restriction of the common drive/sense operation (S_{C34C12}, cf. Fig. 2(b)), the parasitic

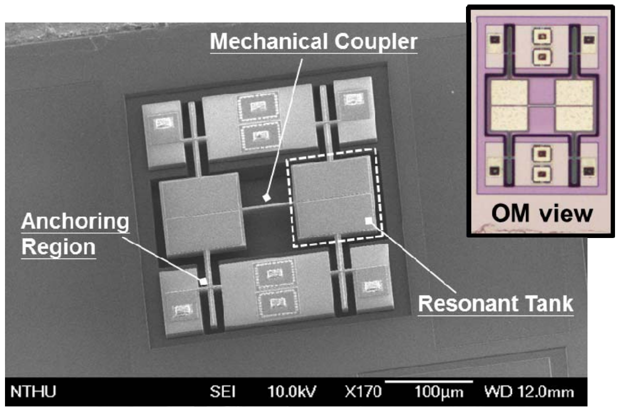

Figure 6: The global SEM and optical photo of a piezo-MEMS filter implemented by InvenSense AlN-on-Silicon platform.

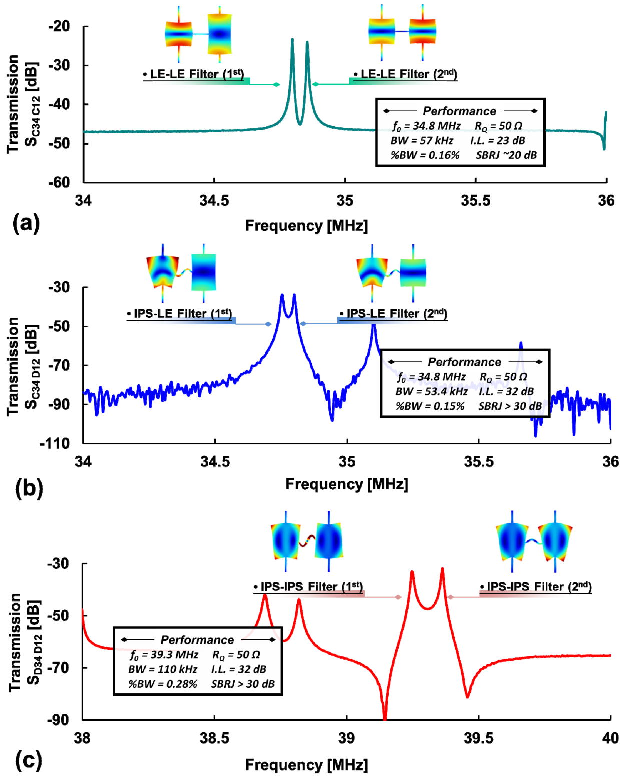

Figure 7: Measured frequency spectra under the (a) LE-LE, (b) IPS-LE, and (c) IPS-IPS filter mode configurations, validating the design concept and simulation results provided in this work. The inset images exhibit the distinct filter modes for each operation.

feedthrough (C_f) limits the performance of the LE-to-LE filter response, thus leading to an undesired in-band notch and inadequate off-resonance rejection, as shown in Fig. 7(a). On the other hand, the IPS-to-LE and IPS-to-IPS topologies feature the expected filter passband with decent stopband rejection due to their differential operation, as illustrated in Fig. 7(b) and (c).

Fig. 8 presents a comparison between raw and terminated spectra of IPS-to-IPS and IPS-to-LE, respectively. Although the IPS-to-IPS filter shows excellent characteristics on feedthrough reduction in Fig. 8(a) by purely differential operation, the main design challenge for practical channel-select applications may come from relatively larger bandwidth and considerable

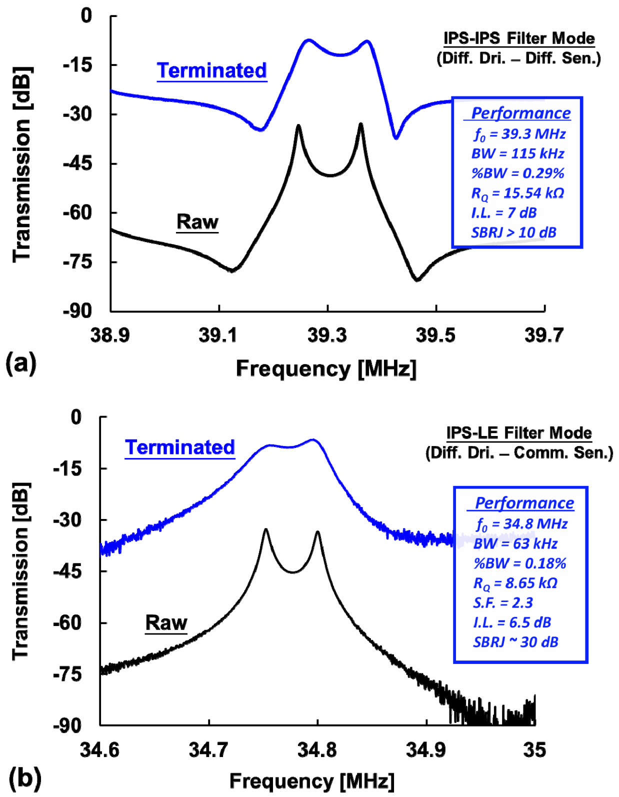

Figure 8: Terminated frequency spectra of the proposed piezo-MEMS filter in the (a) IPS-IPS and (b) IPS-LE coupled mode operations, showing the flatten in-band performance under proper termination R_Q.

fly-back issues after filter termination. Finally, Fig. 8(b) presents a flatten filter response, centered at 34.8 MHz, based on the novel IPS-LE coupled mode design, where the 63-kHz filter bandwidth and 30-dB stopband rejection are achieved under proper filter termination.

CONCLUSIONS

This paper presents a channel selection piezo-MEMS mechanically-coupled filter implemented using InvenSense AlN-on-silicon platform. By the use of silicon/AlN composite structure, the designed resonant tank demonstrates a sufficient Q characteristic when it is excited into multiple in-plane modes, including length-extensional (LE) and in-plane shear (IPS) modes, because of the inherent high quality nature offered by single crystal silicon. Through the qualitative description of the equivalent model, it is apparent that the considerable environmental parasitics ($C_{feedthrough}$) between input and output terminals is problematic for the LE-based filter owing to the common mode operation of constituent resonators. Although the IPS-based filter can create additional notches at both sides of the passband to attain better filter shape factor, it still suffer from the fly-back issue. Therefore, an innovative non-monotonic filter couple mode is firstly proposed to gain the merits from both LE and IPS modes, including (i) differential operation produced by the driving terminal (i.e., IPS mode) to alleviate the undesired feedthrough; (ii) the filter coupler linked to nodal points of the sensing terminal (i.e., LE mode) to obtain a narrow filter passband. Finally, a flat narrow bandwidth of 63 kHz (0.18%BW), centered at 34.8 MHz is achieved under terminated resistance (R_Q) of 8.65 kΩ.

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