Miniaturized Ultrawide Bandwidth WiFi 6E Diplexer Implementation Using XBAW RF Filter Technology

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***Abstract*— In a WiFi 6/6E system, simultaneous operation of bands such as UNII-1 to UNII-4 (HB) and UNII-5 to UNII-8 (UHB) is desirable for high data rate. This presents a critical challenge in which the system needs to have ideally a minimal loss between UNII-1 to UNII-4 while providing > 50dB of isolation from Channel UNII-5 to UNII-8 and vice versa. This paper demonstrates measured hardware in which less than 3 dB of loss is achieved in the pair of passbands and isolation is measured at 50dB level. The typical -3dB bandwidth of this filter pair that is configured in a diplexing mode, is 750MHz and >1GHz respectively. This is achievable by utilizing very high performance XBAW technology.**

***Keywords*—Piezoelectric devices, Microwave filters, Film bulk acoustic resonators, Band-pass filters, 5G mobile communication, Wireless LAN, WiFi 6E.**

I. Introduction

WiFi 6E expands WiFi 6 into wider spectrum above 6 GHz to utilize full capability of Orthogonal Frequency Division Multiple Access (OFDMA), and employment of Multi-user Multiple Input Multiple Output (MU-MIMO). FCC released new spectrum (5.945-7.125 GHz) for unlicensed use. This additional 1180 MHz of new spectrum represents seven additional 160 MHz channels, located within UNII bands 5, 6, 7 and 8. Increased channel bandwidth of 160 MHz, together with enhancements in the 802.11.ax standard, can enable vastly improved WiFi 6/6E performance over WiFi 5. Figure 1 shows a full 6 GHz frequency plan and typical application. To further improve the system performance, a simultaneous operation is employed at HB (5 GHz) and UHB (6 GHz) by using a diplexer. The key challenge is the implementation of a diplex for HB and UHB and provide very high level of isolation as shown in Fig 2. The acoustic wave (XBAW) is the technology of choice for RF signal filtering at 5 GHz and 6 GHz and at lower frequencies [1, 2]. High quality-factor (Q) of BAW resonators enables improved passband loss and steeper filter skirts. XBAW technology enables small filter dimensions, leading to compact systems, improved design tradeoffs and lowered cost. A XBAW filter and technology for 5 GHz WiFi 5/6 was first reported in 2018 [3]. Previous work [2-6] reported WiFi 5/6 BAW filters including a wideband filter covering UNII bands 1 through 3 [4]. This work reports a new WiFi 6E filter for the UNII-5 band, which can be an essential building block necessary for system designers to optimally utilize all available 160MHz channels in the newly released 1180MHz spectrum i.e., in UNII bands 5 through 8. The challenge comes from having to combine these wide band filters so that they provide HB and UHB path while connection to same antenna.

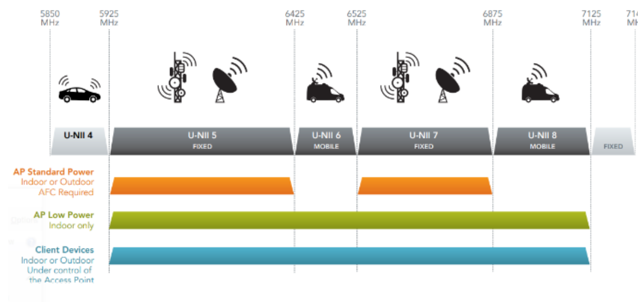

Fig. 1. WiFi 6GHz operation of unlicensed bands.

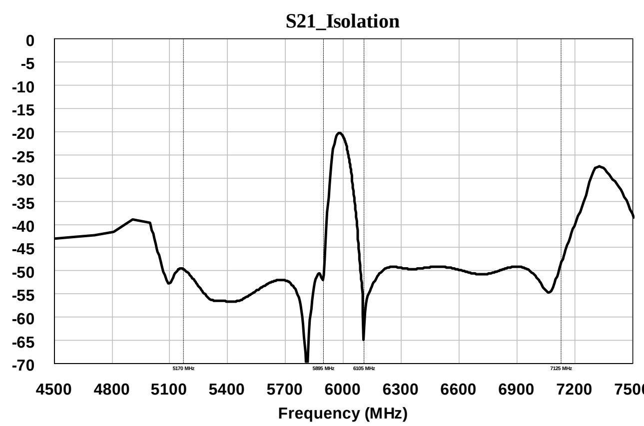

Fig. 2. Challenging isolation requirement for HB and UHB.

As shown in Figure 2, the dominant challenge for this filter is to successfully transmit the HB channel in the while simultaneously rejecting the entirety of UHB. This is conversely true as signal is passed in the UHB while rejecting HB path. This isolation is provided with only 210 MHz gap between HB and UHB. An ultra-steep transition, from 50 dB of isolation with low loss pass bands makes it very challenging.

The key technical challenges in developing this diplexer with HB and UHB include: 1) higher frequency operation leading to thinner piezo-electric stack, smaller resonator size and stronger parasitic effects; 2), ultra-steep transition between pass band requiring very high Q resonators and innovative filter design and, 3) deep and wide adjacent band rejection requiring accurate electromagnetic (EM) and acoustic resonator models and co-simulation of die, laminate, and package. In addition, very high coupling factor is needed to be able to realize such diplexer.

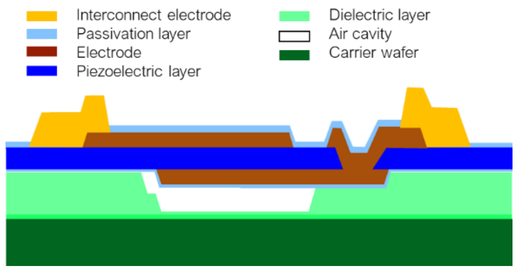

Fig 3. Schematic cross-section of resonator structure in XBAW technology.

II. Device Description and Performance

A. XBAW Technology

The diplexer is realized using a highly doped AlScN piezoelectric material optimized for the specific requirements outlined above, and fabricated using a proprietary and versatile MEMS-based process flow known as XBAW [3]. The super high frequency device presented herein demands AlN films as thin as 200 nm. For such ultra-thin AlN film, not only the growth conditions should lead to formation of strong *c*-axis texture, but also a fine-grain film at the onset of the deposition. The transfer process in XBAW eliminates the need for sputtering the piezoelectric film over a bottom electrode enabling the growth on any arbitrary and high-quality substrate. This is imperative because a smooth and well-textured bottom interface is essential for growth of a highly *c*-axis oriented AlN film. In this work, highly doped AlScN films were reactively sputtered on (100) single crystalline silicon substrates. The use of a single target allows for compositional uniformity across 6” substrates which is readily scalable to 8” substrates as well.

Better oriented films exhibit lower FWHM values which in turn improves the electromechanical coupling. Apart from substrate properties and deposition conditions, FWHM is sensitive to the film thickness. As thickness of the grown piezoelectric film increases, a denser columnar texture is developed leading to improved piezoelectric properties. Degradation of properties in thinner films is associated with a relatively high density of threading dislocations generated at the first few nanometers of the film-substrate interface to release stresses caused by the lattice mismatch [9]. The XBAW process also enables removal of that portion of the piezoelectric film that incorporates a higher defect level.

Another advantage of the XBAW process compared with conventional BAW resonator manufacturing processes is that the resulting piezoelectric film is flat, continuous, and non-interrupted, exhibiting a uniform grain structure and acoustic quality throughout the device. Additionally, since the piezoelectric thin film is grown on a seed wafer, a wide variety of piezoelectric films can be fabricated using essentially the same wafer fabrication process. These films can include epitaxial or single-crystalline AlN, sputtered polycrystalline AlN, and high Sc content AlScN as described in [10-12]. This flexibility allows the material layer stack to be optimized for the specific application and resonators to be tailored to obtain optimum Q and k_{eff}^2. The factors summarized above, together with good thermal conductivity, lead to high Q resonators with superior power dissipation characteristics [12]. The schematic side-view of the final device structure realized by the XBAW process is shown in Figure 3.

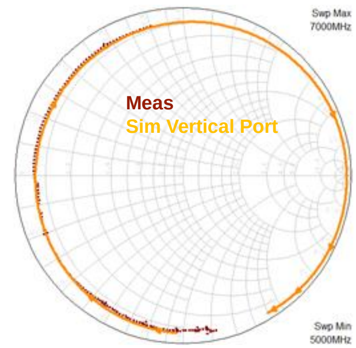

Fig 4. “Q-circle” or s11 plot on a Smith Chart, showing good agreement between measured data and mBVD model.

B. Resonator Performance

S-parameters of 1-port configuration resonators were measured and impact of manifold between intrinsic resonator and measurement probe was corrected by de-embedding. Intrinsic resonator data was fit to a modified Butterworth Van-Dyke (mBVD) model. Good agreement between the measurement and model is shown in Figure 4.

The Bode Q of the measured resonator and its mBVD model were evaluated using the method. The device exhibits a k_{eff}^2 of 20%, calculated using (1).

$$k_{eff}^2 = \frac{\pi}{2}\frac{f_s}{f_p}\cot\left(\frac{\pi}{2}\frac{f_s}{f_p}\right) \quad (1)$$

A comparison of Bode Q extracted from both measured data and mBVD model shows good agreement, as shown in Figure 5 exhibiting $Q_{max} = 530$.

III. Measured Performance

A. Design, Small Signal Performance

The UNII band diplexer is realized through ladder topology and consists of two BAW dies flip mounted on a multilayer laminate utilizing a low loss RF substrate. The laminate contains necessary routing for signal and ground connections that consists high Q embedded coils acting as stretching inductors for shunt resonators. Design methodology involves accurately capturing electroacoustic and EM effects within the die, laminate and packaging.

Resonator electro-acoustic response can be efficiently described by Mason and mBVD models, while EM effects are captured by a 3D model of the die, interconnections, laminate, evaluation board and other details that affect the electrical filter response. Fig. 6 shows measured S21, S31, narrow band performance of UNII-1-to-4 and UNII-5-to-8 diplexer. Fig 7 shows measured insertion loss performance (<3dB) of the diplexer.

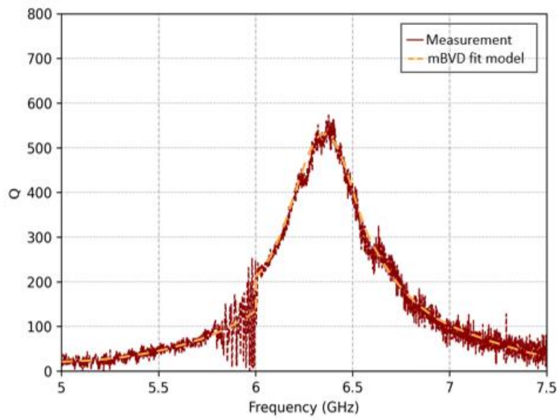

Fig 5. Bode Q plot showing frequency dependency of resonator Q-factor, fitted to mBVD model.

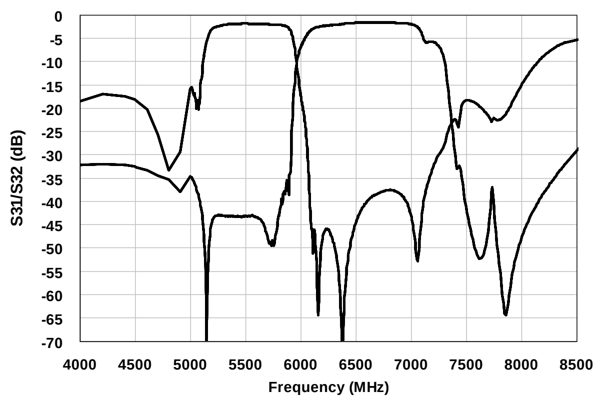

Fig 6. Measured S21, S31 of packaged UNII-1-to-4 and UNII-5-to-8 diplexer.

B. *Power and 2nd Harmonic Performance*

In addition to RF small signal performance, diplexer exhibited adequate power handling capability to sustain the range of input powers experienced during operation and sufficiently low power in the 2^{nd} harmonic frequency range to meet relevant FCC restrictions. Measured small signal performance of the diplexer was observed to degrade by 0.2 dB at input power levels above 25 dBm for both UNII-1-to-4 and UNII-5-to-8 bands. The measured transmitted filter power in the 2^{nd} harmonic frequency range did not exceed -50 dBm at an input power level of 24 dBm. These large signal performance metrics satisfy design requirements of this WiFi 6E UNII-5 filter for the intended application. Future work will address further improvements in power handling capability.

IV. Conclusion

Ultra-wideband diplexer is shown to operate at UNII-1-to-4 and UNII-5-to-8 bands with 750 MHz and >1 GHz -3 dB bandwidths, respectively. Diplexer exhibits <3 dB insertion loss with isolation 50dB across the UNII-1-to-4 and UNII-5-to-8 bands. Large signal of the device shows input power handling of 25 dBm and 2^{nd} harmonic frequency range did not exceed -50 dBm at an input power level of 24 dBm. Fabricated resonators show a maximum quality factor of 500 and a $\boldsymbol{k_{eff}^2}$ of

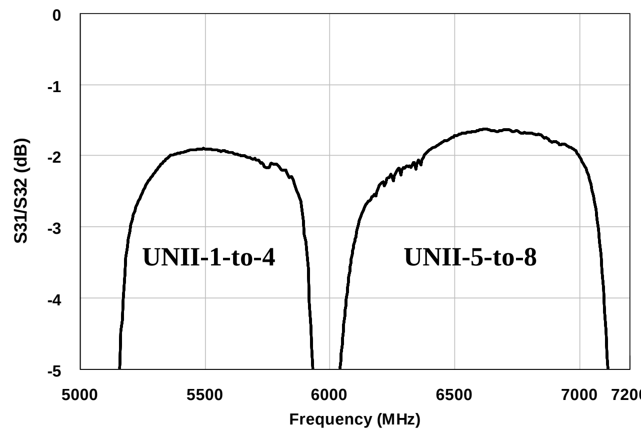

Fig 7. Measured insertion loss of packaged UNII-1-to-4 and UNII-5-to-8 diplexer.

20%. This work demonstrates the potential of the technology described here and promises to address the challenges of future RF filters for UNII bands.

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