Efficient RF voltage transformer with bandpass filter characteristics

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Abstract - **A microwave bandpass filter with a large ratio between the output and the input impedance has been designed and fabricated. Consequently, it functions both as a voltage transformer and a bandpass filter or transfilter for brevity. It represents a two-port micro-acoustic resonator employing Lamb waves in a thin piezoelectric AlN film grown onto a Si carrier substrate with a center frequency of around 887 MHz. The transfilter has a transformer ratio of 10 and a voltage efficiency over 80%. The component has a small size (<0.5 mm^2) and is shown to sustain power levels of 250 mW. It can be used in a variety of cases where both voltage amplification and frequency filtering are required. Examples include: charge pumps in RFID tags, energy scavenging, remotely triggered switches, wake-up radios in wireless networks, stand-by units in home electronics, etc.**

I. Introduction

Passive CMOS-based RFID tags attain energy from the interrogation signal which is rectified and subsequently accumulated over a period of time. Practical reading distances require voltage amplification which is achieved by various variants of the Dickson multistage rectifier[1] also referred to as charge pump, representing a network of rectifying devices (transistors or Schottky diodes) and capacitors. Their voltage efficiency, however, is low and declines rapidly with the degree of amplification.

In a different context, remotely triggered switches (RTS) are needed in remotely controlled devices such as wake up radios in wireless sensor networks, home electronics, etc. The basic circuit of an RTS was proposed by Gu and Stankovic[2] and is illustrated in Figure 1.

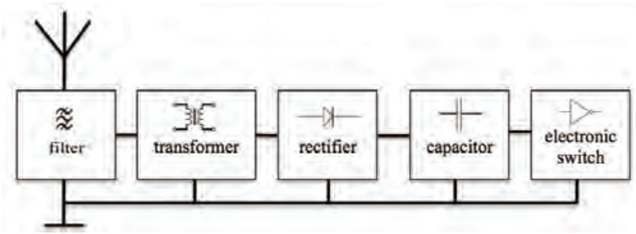


Fig. 1 *Schematic of a remotely triggered switch (RTS)*

The idea is to make use of the energy of the interrogation signal to trigger a low threshold electronic switch. Since the power levels at practical distances are insufficiently low the energy is accumulated over a period of time and stored into a capacitor. A voltage transformer is typically needed to increase both the output voltage and the energy accumulated. A filter is placed between the antenna and the transformer to provide addressing. For instance, several such RTS's, tuned at different frequencies, may be connected in parallel to provide addressing as illustrated in Figure 2.

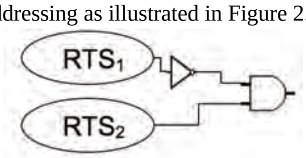
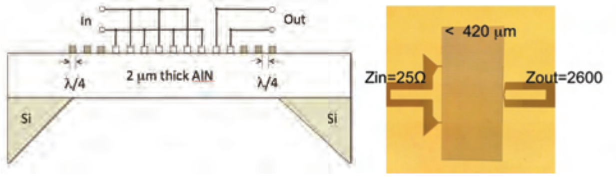


Fig. 2 *Example of a 2-bit RTS, hardcoded as (0,1)*

Notable drawbacks of the RTS described above are its cost and size. To overcome the deficiencies in the above described cases we have designed and fabricated a micro-acoustic bandpass filter with a large ratio between the output and the input impedance which makes it an efficient voltage transformer at the same time. In other words, it is both a transformer and a filter, for brevity also called transfilter. Thus, a single transfilter replaces the first two components in Fig. 1.

II. Experimental

The transfilter represents a 2-port Lamb wave resonator made of a 2.2 µm thick c-textured AlN thin film grown onto a Si carrier substrate. The latter is etched from the backside to release the film and form a free standing membrane. Wave excitation and signal output are realised by inter-digital transducers (IDT) with a 6 µm pitch while energy confinement is achieved by Bragg reflectors consisting of metal strips with the same pitch as that of the IDT. Both the IDT's and the reflectors were made of 300 nm thick Al. For more information on the design of Lamb wave devices see ref. 3. Fig. 3a shows a cross-sectional schematic while Fig. 3b shows a top view of the fabricated component.



a) *b)*

Fig. 3a *A cross-sectional schematic of the transfilter*
Fig. 3b *Top view of the fabricated transfilter*

The area of the transfilter is less than 0.5 mm^2. The transfilter was electrically characterized with a Network Analyser in a 50/50Ω configuration around its central frequency of about 887 MHz. Fig 4a shows the device S_{21} transfer function while Fig. 4b shows its voltage transformer characteristics at center frequency.

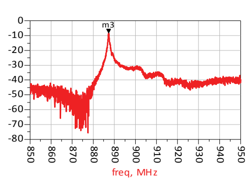


Fig 4a *S_{21} characteristics*

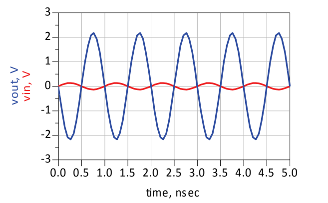


Fig. 4b *Open circuit voltage characteristics*

Specifically, Fig. 4a shows that the component is a bandpass filter with an insertion loss of about -5 dB which after design optimization can readily be brought down to -1 dB. The unloaded Q was 3000 while the device input and output impedance at center frequency were measured to be 25Ω and 2600Ω respectively resulting in a voltage transformer ratio of about 10. The latter is confirmed by Fig. 4b which shows the input and output voltage amplitudes under open circuit conditions. Specifically, an input amplitude of 0.2V is transformed into an output amplitude of 2V with a 180^o phase shift.

To further illustrate the usability of the transfilter in a RTS the above measurements were used to simulate the circuit illustrated in Fig. 5.

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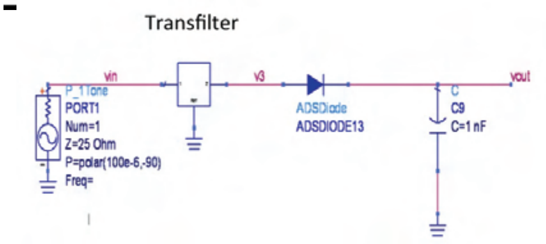

Fig. 5 *Simulated circuit with an input power of 100 μW*

Fig. 6 shows the voltage at the output capacitor as a function of time at center frequency. For comparison, a simulation is also performed for the case without the transfilter.

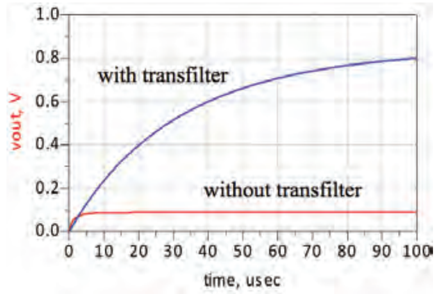

Fig. 6 *Voltage accumulation at the output capacitor at center frequency*

Specifically, for the case without a transfilter the output voltage saturates at around 0.1V irrespective of frequency. In the case with a transfilter the output voltage increases to 0.8V for the initial 100 µs when operated at center frequency, indicating an overall voltage efficiency for the whole circuit of 80% in view of the open circuit transformer ratio of 10. Outside center frequency the voltage at the output capacitor is practically zero as also seen from Fig. 4a which shows that the signal is significantly attenuated outside the passband. Hence, the circuit illustrated in Fig. 5 operates as a highly efficient RTS. Further, recalling that the center frequency of the transfilter is determined by the pitch of the IDT, that is lithographically, it is seen that a number of such transfilters operating at different center frequencies can be fabricated on a single chip having a common input and separate outputs. In other words, addressing in the context of Fig. 2 is readily and efficiently achieved. Naturally, the complete device (the whole set of transfilters) needs to be carefully designed as each separate transfilter sees the rest as a net parasitic capacitance connected in parallel affecting thus the bandwidth of each transfilter. As noted above, the transformer ratio is determined by the ratio between the output and the input impedance, which can be varied in a wide range. Thus, assuming a limited interrogation power of 10 mW in the ISM band and interrogation distances of several meters, output voltages in the order of several volts become feasible[2]. This, of course, would be at the expense of longer integration time intervals in the range of milliseconds. In this context, truly passive RTS become possible by employing capacitive MEMS switches which require pull-in voltages of the order of several volts[4]. Fig. 7 illustrates schematically such a truly passive, addressable RTS.

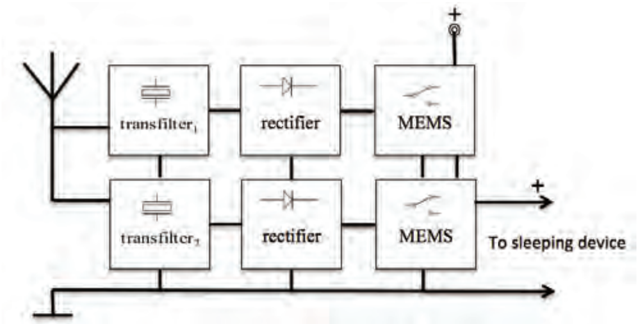

Fig 7. *A schematic of a truly passive, addressable RTS*

In practice, a drain resistor connected in parallel to each MEMS switch is required to reset the switch to its initial state. Hard coding is achieved by both normally open '1' and normally closed '0' MEMS switches.

It is noted that the thin film electro-acoustic technology is a low cost technology indicating low transfilter fabrication costs, most likely in the order of 10 cents in large volumes. In addition, it is fully compatible with the IC technology suggesting that transfilters can be fabricated on top of an IC provided the areas of the two are comparable. Naturally, the area of the transfilter is inversely proportional to frequency.

With respect to semiconductor charge pumps the transfilter excels in terms of efficiency, cost and size. Another distinct feature is the fact that there is practically no initial energy accumulation, unlike charge pumps where all coupling capacitors need to be sequentially charged. A further advantage of the transfilter is that it is a linear device operating at all input power levels, practically eliminating the so called "dead zone" of charge pumps. Not the least, for a full cycle rectifier the number of forward-biased rectifying devices in this case is 2 in contrast to charge pumps where this number is proportional to the degree of voltage amplification. Noteworthy, the transfilter has been operated at a power level of 250 mW for a period of several weeks without degradation.

Other possible use of the transfilter includes stand-by units in remotely controlled home electronics such as TV, video, etc, wake up radio circuits in wireless sensor networks, addressable passive (non-IC) sensors, RFID tags, impedance matching, etc. Noteworthy, micro-acoustic components can withstand high temperatures and harsh environments such as ionizing radiation widening their field of application to areas non-traditional to semiconductor electronics.

Finally, it is noted that the device is not limited to Lamb waves nor is it limited to thin AlN films. Other acoustic waves, such as surface, bulk, etc may also be employed to achieve similar if not better performance. Further, piezoelectric materials with high piezoelectric constants such as $LiNbO_3$, $LiTaO_3$, AlScN[5], etc may also be employed to achieve large bandwidths.

III. Conclusions

A highly efficient, small size, low cost RF voltage transformer with filter functionality has been designed, fabricated and electrically characterized. A voltage transformer ratio of 10 at a center frequency of 887 MHz has been demonstrated. An insertion loss of -5dB has been measured. Alternative designs are expected to decrease the insertion loss to around -1dB while higher transformer ratios are readily achievable. A wide range of possible applications has been identified.

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