1. Introduction

Wireless communication systems in GHz band such as W-CDMA [1], Bluetooth [2] OFDM [3], etc., are widely developed toward popularization of the wireless network. The goal of the wireless network has been called as Ubiquitous Network. The Ubiquitous Network provides easy network access for consumer on the basis of optical fiber backbone network and local wireless access. In Japan, 2.4GHz ISM band has been approved for consumer wireless data communication based on spread spectrum (SS) wireless system since 1993 [4,5]. The 2.4GHz ISM band is expected to be used for consumer wireless access to the Internet.

Surface acoustic wave (SAW) devices have a potential for being used to compact radio frequency (RF) components in GHz band. SAW matched filter for SS communication systems is suitable for terminal equipment because of its inherent low power consumption.

We have already developed single crystal Aluminum-Nitride (AlN) film on Al2O3 substrate using metal organic chemical vapor deposition (MOCVD) method [6-9]. Zero-temperature coefficient of AlN/Al2O3 combination on the 5×5mm² scale wafer has been found by authors group [10]. Because of high SAW velocity of 5910m/sec, inter-digital transducer for 2.4GHz devices can be fabricated using conventional photolithographic technology. Single crystal AlN film with flatness of less than 1% has been successfully deposited on 2-inch diameter wafer using MOCVD.

Using AlN/Al2O3 combination, SAW filter for 2.4GHz has been fabricated and evaluated [11]. Furthermore, 2.4GHz SAW matched filter for SS modem has been fabricated using AlN/Al2O3 [12,13]. 11-chip Barker code with chip rate of 22Mchip/sec has been used.

We have already proposed and implemented 2.4GHz wireless modem using the SAW matched filter [12]. Using delay detection in RF band with SAW matched filter and SAW delay line, compact card size modem has been developed for practical use.

In this paper, two applications have been shown using SAW matched filter. At first, implementation of packet CDMA modem using the SAW matched filter [14] has been described. The feature is combination of rapid synchronization by SAW matched filter and low power despreading by inline correlator. 4-channel multiple access has been confirmed with no degradation of bit error rate (BER) in measurement of bench test. Secondary, SS wireless switch using the SAW matched filter [15] has been described. Low power consumption SS wireless switch of 100µW has been developed. It is confirmed that implemented SS wireless switch has long battery life of 10 years and wide communication range of 30m can be obtained.

2. Fabrication of SAW matched filter for 2.4GHz SS band

Using high SAW velocity material, wideband GHz matched filter including carrier can be fabricated. On the other hand, SAW device has degradation of correlation function due to propagation loss. Therefore, short code matched filter with high chip rate in GHz band is suitable application for SAW devices.

![Figure 1: Structure of AlN/Al2O3 SAW matched filter.](image-url)
Figure 1 shows structure of AlN/Al₂O₃ SAW matched filter. Single crystal AlN film has been deposited by MOCVD method using trimethyloxaluminum (TMA) and ammonia (NH₃). For 2.4GHz operation, line and space of inter-digital transducer of 0.6µm can be fabricated using conventional photolithography. Tapping pattern of electrode on delay line is determined by 11chip Barker code.

Figure 2 shows the photograph of the SAW matched filter. Figure 3 shows impulse response of the fabricated SAW matched filter. 11-tapping peak was obtained. Propagation loss was clearly estimated 9dB, which corresponds to 35dB/cm.

For improvement of correlation performance, weighted tapping SAW matched filter has been proposed. Figure 4 shows the weighted tapping layout. Number of pairs on each tapping electrode has been decided from the propagation loss of the standard matched filter. Figure 5 shows impulse response of the implemented matched filter using weighted tapping pattern. Degradation of correlation function due to propagation loss was improved by weighted tapping pattern. Improvement of processing gain is about 5dB more than that of SAW matched filter using standard tapping pattern.

3. Implementation of the packet SS-CDMA modem using SAW MF

Conventional CDMA modem has a correlator for de-spread the spreading sequence. Although a sliding correlator has a feature of low power consumption, long acquisition delay for synchronization is needed in the case of long spreading code. Using a matched filter, rapid synchronization can be obtained. Digital matched filter has large power consumption in the case of high operation clock. Additionally, there is long integration delay time for long spreading code. SAW based matched filter has no power consumption inherently. However, correlation function of spreading code degrades due to propagation loss along with the delay line.

We have proposed packet SS-CDMA system using both short code SAW matched filter for synchronization and in-line correlator for de-spread. RF front-end short code SAW matched filter has great merits of correlation including carrier, rapid correlation in 1-code cycle, no power consumption and high efficiency. The combination of SAW matched filer and in-line correlator has an advantage of both rapid synchronization and low power operation. Furtermore, rapid synchronization is needed for wireless
packet transmission such as wireless Internet access. As shown in Fig. 6, transmission frame consists preamble symbols and information symbols. The preamble symbols are 10 symbols and the information symbols are 500 symbols. 11-chip Barker code with chip rate of 22 MHz is employed for spreading code of the preamble symbols, so that burst transmission is carried out in the synchronization symbols. Since the preamble symbols are synchronized with symbol clock, both chip and symbol synchronization can be simultaneously obtained by the detection of the Barker code using SAW matched filter. 64-chip orthogonal m-sequence is employed in the information symbols for CDMA with 63-channel assignment.

The receiver has synchronization block and de-spreading block as shown in Fig. 7. Received signal is input to SAW matched filter of the synchronization block. SAW matched filter detects the 11-chip Barker code. Chip and symbol synchronization is established by detecting correlation peaks output from the SAW matched filter. In the de-spreading block, information symbols are de-spread using in-line correlator. De-spreading code is generated using the timing from the synchronization block. Finally, baseband data is obtained after quadri phase shift keying (QPSK) demodulation. Multi-channel information is demodulated using parallel in-line correlator and QPSK demodulator.

BER performance has been measured on the additive white gaussian noise (AWGN) channel as shown in Fig. 7. Digital circuit of modulation and demodulation has been implemented using field programmable gate array. 4-channel multi-channel transmission performance was measured. Figure 8 shows the BER performance as a function of $E_b/N_0$. $E_b$ has been decided by the power of the transmitted signal. $N_0$ has been decided by the measurement of noise power at the receiver input port. The number of multi-channel was from 1 to 4. Solid line is the theoretical curve of QPSK demodulation with coherent detection. When the number of multi-channel is 1, degradation of $E_b/N_0$ from the theoretical curve is confirmed to be less than 1dB. Furthermore, when the number of multi-channel is 2, 3 and 4, there is no degradation of $E_b/N_0$ from the 1-channel transmission. This means the SAW matched filter based packet SS-CDMA modem has excellent performance for multi-channel transmission.
4. Implementation of SS wireless switch using SAW matched filter

In this section, ultra-low power application using SAW matched filter has been described. Requirement of wireless based remote measurement system increases in order to improve efficiency of periodical measurement. Figure 9 shows schema of a remote measurement system. Remote measurement system consists of information terminal for a meter reader, wireless switch, power switch, data transmitter and power supply. Usually, power switch is kept off, so that data transmitter does not consume the power. Information terminal transmits a trigger signal when the meter reader requires data. The wireless switch turns on the power switch after detecting the trigger signal. The data transmitter sends data of to information terminal of the meter reader. Finally, the power switch is turned off after sending data.

Power consumption of the remote measurement system is decided by the waiting current of the wireless switch. This is because the data transmitter works less than 1 second in a month. Mean power consumption of the data transmitter is less than 0.03\(\mu\)W even if the peak power consumption is 100mW.

Conventional wireless switch is based on infrared light or single carrier continuous wave (CW). Although the infrared light based switch operates low power consumption and low cost, the signal path shadowing degrades the triggering performance. The CW based switch has tolerant against shadowing in addition to low power consumption and low cost. However, error operation due to radio interference from other electronics equipment exists.

SS wireless switch has resistance of radio interference because of certification using spreading code. Main issue of implementation of SS wireless switch is power consumption of matched filter. Using digital matched filter or IF SAW matched filter, power consumption cannot be reduced because down converter and local oscillator is necessary to implement the receiver. If down converter has the power consumption of 10mW, the battery life is less than 1 year with 2.7Ah battery.

We have proposed RF front-end SAW matched filter based SS wireless switch. We have already developed 2.4GHz SAW matched filter using AlN/Al\(_2\)O\(_3\) combination as described in section 2. The RF front-end SAW matched filter does not consume any power inherently.

For trigger signal, 11-chip Barker code with chip rate of 22Mchip/sec is used. Center frequency is 2.484GHz, which is center frequency of SS band in Japan. Figure 10 shows designed block diagram of the SS wireless switch using the SAW matched filter. SAW matched filter is directly connected to antenna without RF amplifier. When the trigger signal is coming in, correlation peaks with 2MHz cycle appear as output signal of the SAW matched filter. Envelope detection using shotky diode is carried out in order to shape the correlation peaks. The shaped correlation peaks are filtered and accumulated in the accumulation block. In detector and accumulation block, high impedance circuit design is employed in order to suppress the current consumption. For accumulation, quarts resonator is used, because the quarts resonator with high Q is suitable for high impedance design and. 2MHz sine wave is amplified using low power CMOS inverter, which is used for low
power application such as a wristwatch. CMOS amplifier and decision circuit have intermittent operation of 0.5 sec period. The decision circuit output the signal to turn on the power switch, when 2MHz sine signal is detected.

SAW matched filter and accumulation block use no current, and decision block uses less than 0.2 µA. Power consumption of SS based wireless switch is decided by the bias current of envelope detector and number of CMOS inverter. 3 types of wireless switches have been implemented, 10µW, 100µW and 1mW. The power consumption of 100µW corresponds to a battery life of 10 years when Li-Ion battery (2.7Ah) is used. Figure 11 shows photograph of the implemented SS wireless switch. Bias current of envelope detector can be controlled by variable resistance. In this work, detection block have been implemented using discrete components. The size of detection block can be shrunken by developing custom LSI.

Figure 12 shows the block diagram for measurement of sensitivity using implemented SS receiver block. In this measurement, sensitivity is defined as the minimum output power level of signal generator when the trigger signal receiver detects the trigger signal. Table 1 lists the sensitivity of each SS wireless switch. With increase in current consumption, the sensitivity of the SS wireless switch improves. In the case of power consumption of 100µW, the sensitivity is −60dBm.

Communication range has been estimated using equation of propagation loss \( L_d \) on free space propagation [16].

\[
L_d@2.484GHz[dB] = 36.04 + 20\log(d),
\]

where \( d \) is propagation distance. Dipole antenna is assumed. The transmitted power is 20dBm.

Figure 13 shows the estimated communication range depending on the sensitivity. Transmitted power is assumed 10dBm. In the case of 100µW, estimated communication range is 158m. The communication range of 158m is enough value for being used to wattmeter remote measurement.
5. Conclusion

We have demonstrated the two kind of application using 2.4GHz AlN/Al$_2$O$_3$ SAW matched filter.

Packet SS-CDMA modem using the SAW matched filter has been designed and implemented. Simple receiver structure with separation of synchronization and de-spreading has been proposed. It is confirmed that implemented modem has a performance of 4-channel transmission with no degradation.

SS wireless switch using SAW matched filter with RF front-end operation has been described. When the Li-ion battery of 2.7Ah is used, long battery life of 10 years and wide communication range of 30 m is successfully obtained. This result shows that SS wireless switch has a suitable performance for remote measurement system.

It is confirmed that 2.4GHz RF front-end SAW matched filter for short code based on AlN/Al$_2$O$_3$ combination has a great performance to be used as a correlator of SS wireless application.

We can strongly expect that the proposed packet SS-CDMA method will become a key technology of over 100 MHz wideband CDMA for next generation wireless access system. Development of GHz wideband SAW device for chip synchronization is strongly required for a very wideband SS technology.

References


