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Drift-free FBAR oscillator using an atomic-resonance-stabilization technique

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***Abstract*— We developed a thin-film bulk acoustic resonator oscillator (FBAR-OSC) with drift-free and excellent frequency stability. The FBAR-OSC outputted the 3.5 GHz band oscillation and successfully stabilized it employing the coherent population trapping (CPT) resonance of clock transition in Rb alkali metal atoms. As a result of the stabilization, the temperature drift was canceled, and the frequency fluctuation was suppressed to 0.5 ppb or less in the measurement time of 10^4 s.**

Keywords—FBAR, oscillator, stabilization, CPT resonance, rubidium

I. Introduction

In relation with the redefinition of a second in the international system of units (SI) using the optical frequency standard such as the Sr optical lattice clock, the frequency stability in the backbone or backhaul of a communication network is expected to improve by more than five digits in the 2020s (on the order of 10^{-16} to 10^{-18}) [1][2]. Thus, the oscillator or clock in consumer devices should be required to have frequency stability improved by five digits or more, and it is expected that frequency stability on the order of 10^{-11} to 10^{-13} will be required.

Turning eyes to beyond-5G (Post-5G) systems, wireless communication will always require increased capacity and speed, low latency, and high terminal mobility, as shown in Fig. 1. In particular, these enhancements are indispensable in the fields of virtual reality/augmented reality (VR/AR) and self-driving, where growth in the future is expected. The increase in communication capacity and speed should be solved by employing a high-frequency band above 6 GHz and expanding the frequency bandwidth [3]. Also, high mobility and latency reduction should be accomplished by edge computing that deploys small servers close to users.

However, the improvement of latency has a higher technical hurdle than increasing the capacity or speed. It will be impossible for the latency to be finally reduced to zero even if edge computers/servers are widespread with high density. A feasible solution can be found in the field of relational databases (RDBs) where decentralization is already in progress. In the advanced decentralized RDB, a GPS receiver and an atomic clock are installed in each server, the latency is highly managed,

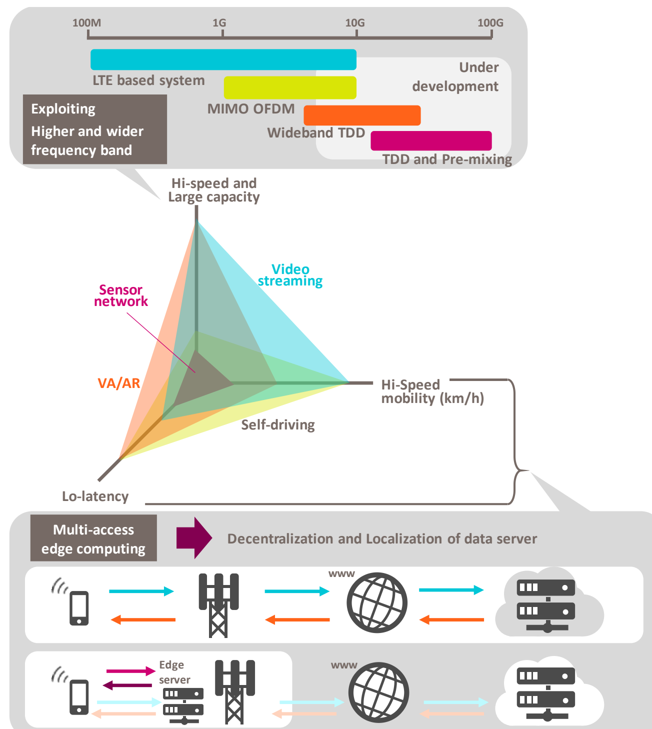


Fig. 1. Relationship between user needs, specifications and technology in the 5G and 5G+ wireless systems.

and the exclusive processing during replication is efficiently performed [4]. We suppose that it is possible to augment the concept of the latency management to compact edge servers and even individual devices. In such a prediction, the integration and miniaturization of high-precision clocks, counters, and GPS chips will be a hot area in the development of consumer RF components.

To assign these potential needs for a highly stable clock in wireless communications, we attempt to develop a film bulk acoustic resonator oscillator (FBAR-OSC) suitable for integration with an atomic resonator. Specifically speaking, in this report, we describe a highly stabilized FBAR oscillator at

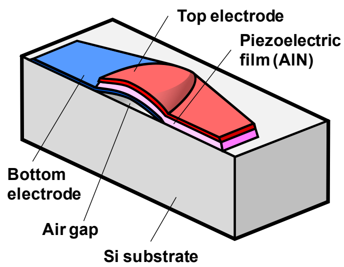
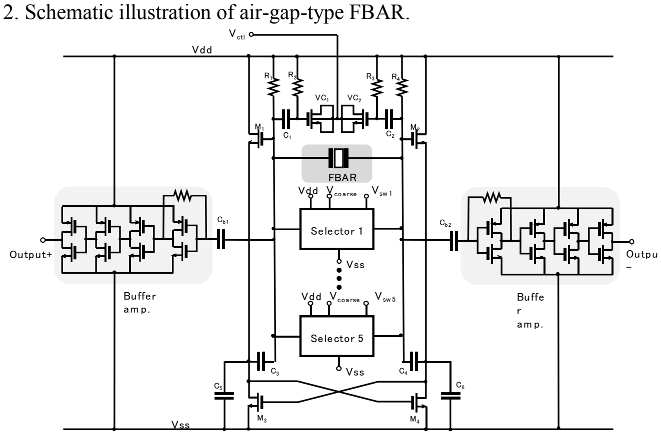
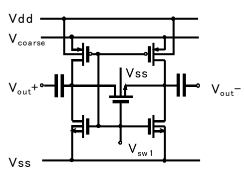


Fig. 2. Schematic illustration of air-gap-type FBAR.



(a)



(b)

Fig. 3. Circuit topology of FBAR oscillator: (a) schematic of oscillator with frequency tuner, (b) detail of switch selector.

the 3.5 GHz band employing the coherent population trapping (CPT) resonance of alkali metal atoms such as Rb. Most of the components in our system were fabricated using Si-based microfabrication technology and will be easy to integrate into the chip level.

II. FBAR Oscillators

The FBAR has a structure in which a piezoelectric thin film is sandwiched between electrode thin films with high acoustic impedance (see Fig. 2), and its mechanical resonance operation is based on a principle similar to that of a quartz resonator [5]. Unlike the quartz resonator manufactured by polishing, the FBAR is manufactured using typical MEMS technologies such as film deposition and photo-processing; thus, it has excellent compatibility with CMOS circuitry [6][7]. Also, the FBAR is suitable for high-frequency operation exceeding the GHz band with a high Q factor of more than 1000, since it is a thin-film device [8][9][10].

The FBAR is widely used today as a multiplexer filter closest to an antenna in the front-end circuitry, and its frequency range is being expanded up to sub-6 GHz owing to the recent increase of communication specifications. To stabilize the FBAR oscillation by utilizing the hyperfine structure transition (clock transition) of the alkali metal atom ^{87}Rb or Cs, it is necessary to tune up the frequencies to $f_{clock\_Rb}/2$ = 3.417 GHz or $f_{clock\_Cs}/2$ = 4.596 GHz, respectively. These frequencies are compatible with the resonant frequency of commercial FBARs. In this study, we prototyped a high-frequency oscillation circuit for an Rb atomic clock using this FBAR as a frequency selection element.

As a result, an extremely simple high-frequency oscillator without a frequency multiplier or a phase-locked loop (PLL) has been realized, and sufficient progress has been made in miniaturizing an atomic frequency standard [10]. However, to use a mass-produced FBAR, it is necessary to enhance the frequency tunability to certainly catch the narrow linewidth of atomic resonance. In this study, as shown in Fig. 3, multiple frequency selectors composed of MOS switches, pull-up transistors, and pull-down transistors are integrated to enhance the resonance frequency tolerance of FBARs. The oscillator chip was implemented using a 65 nm CMOS process and connected to the FBAR chip with Au wires.

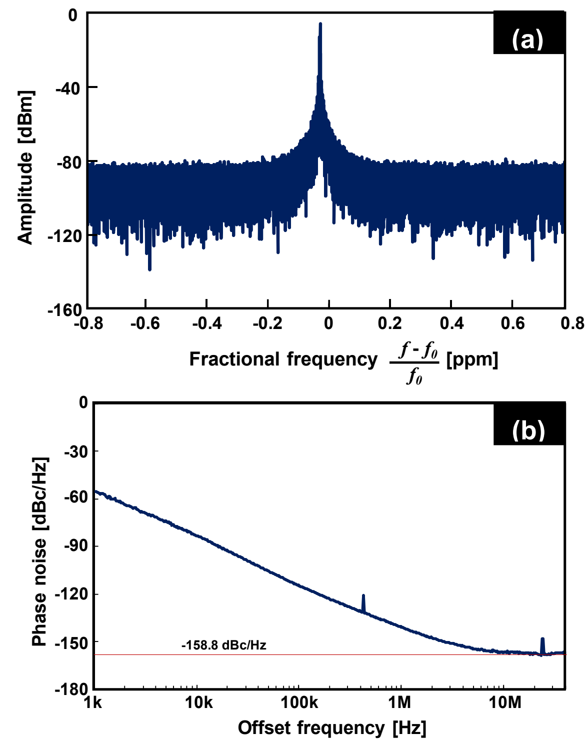


Fig. 4. Characteristics of BAW oscillator: (a) oscillation spectrum (f_0: oscillation frequency 3.17 GHz), (b) phase noise.

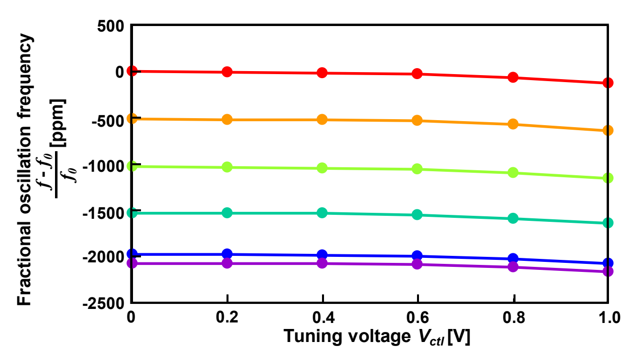


Fig. 5. Characteristics of oscillation frequency tuning: ● All selectors off, ● one selector on, ● two selectors on, ● three selectors on, ● four selectors on, ● all selectors on, f_0: original oscillation frequency.

Figure 4 shows a frequency spectrum and phase noise characteristic of a prototype FBAR-OSC. A clear peak is observed. The floor level of phase noise was −158.8 dBc/Hz. Figure 5 shows a result of tuning with a CMOS varactor and a selector. From this result, the complementarity of fine and coarse tuning of oscillation frequency is confirmed. This characteristic can be exploited to compensate for the initial variation of frequency originating from the manufacturing process of the FBAR.

III. ATOMIC RESONANCE STABILIZATION

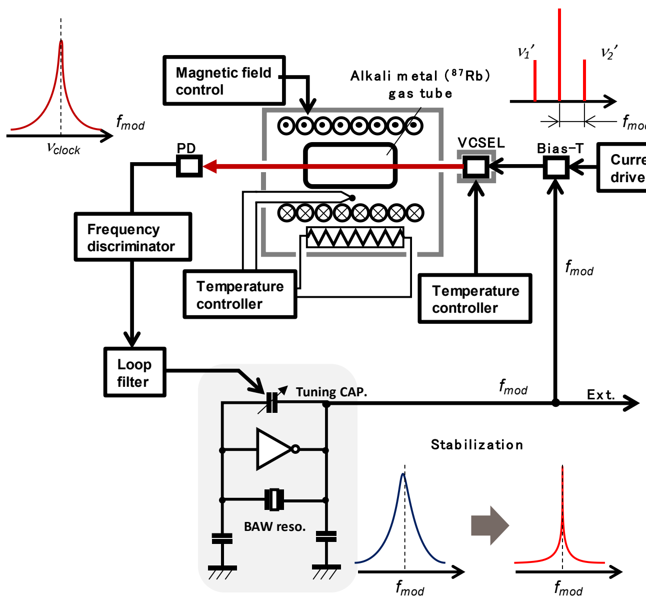


Fig. 6. Block diagram of atomic resonance stabilization.

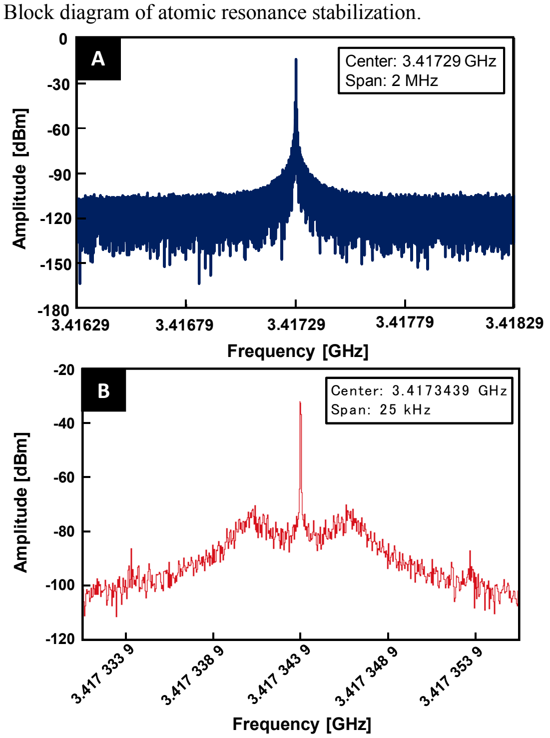


Fig. 7. Oscillation characteristics of FBAR oscillator, A: frequency spectrum of the FBAR oscillator, B: frequency spectrum of the atomically stabilized FBAR oscillator.

Figure 6 shows a block diagram of the FBAR-OSC system with an atomic resonance stabilization loop. In this illustration, ^{87}Rb gas is packed in a glass tube. However, in a practical system, a cylindrical MEMS cavity of 3 mm diameter and length was adopted [11][12][13]. Figure 7A shows the spectrum of the FBAR-OSC, and Figure 7B shows that when the FBAR-OSC was stabilized to the atomic resonance. Note that the spans of A and B are 2 MHz and 25 kHz, respectively. These results show that the phase noise at low frequency (<2 kHz) is considerably suppressed by the stabilization to the atomic resonance. To verify the frequency stability, the temporal change in the oscillation frequency was measured and is shown in Fig. 8. In the free-running of the FBAR-OSC, we can see the frequency drifts that reflect the temperature variation of the FBAR-OSC. In contrast, the stabilization to the atomic resonance realizes a drift-free behavior with a short-term fluctuation of less than 0.5 ppb.

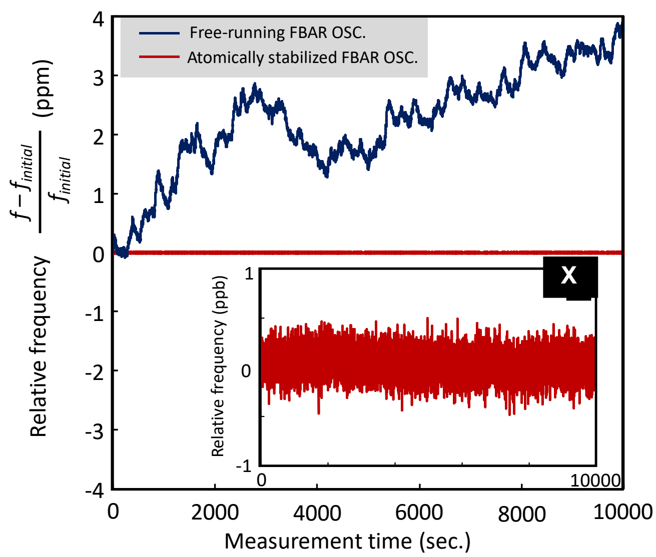


Fig. 8. Temporal traces of oscillation frequency: closed-up characteristic of atomically stabilized FBAR-OSC (X)

IV. CONCLUSION

In this study, we developed a thin FBAR-OSC that oscillates in the 3.5 GHz band, and demonstrated a stabilization method using the CPT resonance of ^{87}Rb. The FBAR-OSC was designed to eliminate the screening in the wafer process, and multiple-capacitance selectors and a varactor were integrated on the CMOS amplifier chip. As a result of the stabilization, the temperature drift of the FBAR-OSC was canceled out, and the oscillation frequency fluctuation was successfully suppressed to the 0.5 ppb level in the measurement interval of 10^4 s. Our system was mainly constructed using silicon-based microdevices. This means that the atomic frequency standard of the microwave band can be integrated into the chip level by exploiting MEMS technologies. Also, this concept gives a new vision wherein the construction of an advanced synchronous communication network can be backed up from the device level, and the latency in the wireless communication system can be efficiently managed from the edge server and even the device level.

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