Super-high-frequency-band injection-locked two-divider oscillator using thin-film bulk acoustic resonator

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Introduction: We are developing an on-chip atomic clock system based on coherent population trapping (CPT) resonance [1–3]. The bottlenecks hindering the on-chip integration are the power consumption of the microwave oscillator and the area consumption of the lock-in amplifier implemented by a commercial microcontroller [4]. Therefore, we have developed a microwave oscillator using a thin-film bulk acoustic resonator (FBAR) and have also started developing a self-oscillation-type atomic clock system [5]. By using the FBAR, one can simply obtain a microwave oscillation without the need for a complicated phase-locked loop (PLL) using a quartz oscillator for frequency multiplication [3]. Also, in the self-oscillation system, it is not necessary to digitally discriminate against the locking state of the atomic resonance. Thus, the area-consuming microcontroller can be omitted [6].

The frequency two-divider is essential for constructing the feedback loop of the self-oscillating CPT atomic clock system. When using the hyperfine structure of 87Rb as a frequency standard, the clock transition frequency of 87Rb of 6.824 GHz to provide a laser modulation signal at 3.417 GHz for an on-chip coherent population trapping atomic clock system. To obtain high frequency stability and low-phase noise with low power consumption in the super-high-frequency band, a thin-film bulk acoustic resonator is used instead of the conventional LC tank circuit. The fabricated oscillator operated well with a power consumption of 4.5 nW. The maximum lock range was 1.5% in fractional frequency. Also, unlike the conventional injection-locked divider oscillator with an LC tank, the bifurcation of the lock range width was observed when sweeping the injection power of the 6-GHz-band signal, and in the down sweep, the locking operation was maintained even at an injection power of −20 dBm.

Design and fabrication of FBAR ILDO: We developed a direct-injection-type frequency divider incorporating the FBAR. An ILDO is classified into a tail injection type or a direct injection type, and the latter is suitable for the reduction of power consumption [8, 9]. The direct ILDO is composed of a cross-coupling CMOS inverter and an LC tank circuit [10, 11]. Figure 1 shows our circuit schematic. In our ILDO, an acoustic resonator is incorporated instead of the LC tank, and the periodic signal in the super-high-frequency (SHF) band is directly injected into this acoustic resonator.

We used the FBAR as an acoustic resonator since it can be fabricated on the active circuit and shows high-Q resonance reaching 1000 even at the SHF band [12–14]. The FBAR has a thin-film stack structure in which the upper and lower electrodes are fabricated on both sides of a piezoelectric AIN thin film (Figure 2a). Such a stacked structure is deposited on the substrate and has an air gap against the substrate for acoustic isolation, and the structure is fabricated by a sacrificial layer etching technique [15, 16]. The resonance frequency of the FBAR is preferentially tuned to around 3.417 GHz, which corresponds to the laser modulation frequency to acquire the CPT resonance, but in this prototype production, precise frequency trimming has not yet been performed. The actual resonant frequency fluctuated in each FBAR and was around 3.19 GHz. Thus, the oscillation frequency also fluctuated slightly above the resonant frequency of 3.19 GHz. The data shown in the sections below were normalized with the actual oscillation frequency as f0.

The cross-coupling CMOS inverter was designed on the basis of 65 nm CMOS rules and manufactured in the external fab. The ILDO has a two-chip configuration in which the FBAR and CMOS chip were connected by wire bonding, as shown in Figure 2b. The substrate thickness of the CMOS chip was adjusted in the postprocess to minimise the wire length and suppress the parasitic inductance or resistance. The FBAR
size is reduced to be inversely proportional to the frequency and can show a size advantage against the on-chip inductor in the SHF band [13, 17, 18]. Thus, the FBAR would be integrated above the CMOS circuit in the future [19, 20].

Response for second-harmonics injection: To confirm the frequency division operation from the 6 GHz band to the 3 GHz band, we attempted to inject the SHF band signal into the FBAR ILDO. The applied voltage range was from 0 to 1.3 V since the CMOS circuit was implemented using 65 nm CMOS technologies. To keep this range, the signal injected into the FBAR ILDO was an SHF signal with a power of 3 dBm biased by the DC voltage of 0.975 V. The balanced output from our device was measured with a spectrum analyser through an external balun module. Figure 3 shows an experimental result. The injected second harmonic was successfully divided by two. Figure 4 shows the oscillation spectrum obtained by the frequency division. This spectrum was reflected from that of injected harmonics. Thus, when incorporated into the atomic clock system, the divided signal can be greatly improved by the narrow linewidth of atomic resonance.

Locking range of divide-by-2 mode: The divide-by-2 mode shown in Figure 3 is not only observed just on second-harmonics injection, but it also has a certain width in the vicinity of the harmonics. This range of locking is also found in the ILDO with the conventional LC tank [21]. It is also known that a characteristic region called the Arnold tongue is drawn when sweeping the injection signal power, where the locking range becomes wider as the injection signal power increases [21, 22]. The ILDO that we developed had a similar locking region. However, it also has a certain width in the vicinity of the harmonics. This range of locking is also found in the ILDO with the conventional LC tank [21].

Since the threshold power was shifted owing to the design of the FBAR, the bifurcation is considered to be the origin of the non-linearity inherent in the FBAR. Recently, in the research of FBAR, non-linearity due to the thermal transition in the thin-film stacked structure under a high-power RF signal has been reported [23, 24], and further investigation on it is required. Figure 6 shows the Arnold tongue obtained from our ILDO when sweeping down the power of the injection signal. The maximum locking range was 97 MHz (fractional bandwidth of 1.5%) regardless of $Z_0$.

In the FBAR ILDO, power consumption was quite low at 45 nW when the frequency division mode well occurred. This is because the ILDO has a simple configuration that does not include power-consuming frequency-tuning devices such as varactors and switchable capacitor networks [25] and it is operated quasi-passively in the divide-by-2 mode.

Conclusion: Aiming to achieve the on-chip CPT atomic clock, we developed an ILDO to efficiently convert a 6-GHz-band signal to a 3-GHz-band signal with low power consumption. The 6-GHz-band signal corresponds to the clock transition frequency of the $^{87}$Rb atom, and
the 3-GHz-band signal is used for the laser modulation to detect the CPT resonance. Our ILDO was incorporated with a high-Q FBAR instead of a conventional LC tank for handling the narrow linewidth of the atomic resonance. The FBAR ILDO traced the injected 6-GHz-band signal, successfully converted it to half the frequency, and indicated a maximum locking range of 97 MHz (fractional bandwidth of 1.5%). The locking range had an Arnold-tongue-like region well known in conventional non-linear circuits. Additionally, in this evaluation, bifurcation was confirmed in the width of the lock range against the sweep direction of the injection power. When the power was swept downward, the finite lock-range width could be kept up to \(-20 \text{ dBm}, \) which is the lower limit of the injection power in our experimental setup. Power consumption with the divide-by-2 mode was 45 mW when the source voltage was 1.3 V.

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References

1. Cyr, N., Têtu, M., Breton, M.: All-optical microwave frequency standard: a proposal. *IEEE Trans. Instrum. Meas.* **42**(2), 640–649 (1993). https://doi.org/10.1109/19.278645
2. Jau, Y.Y., Happer, W.: Push-pull laser-atomic oscillator. *Phys. Rev. Lett.* **99**, 223001 (2007). https://doi.org/10.1103/PhysRevLett.99.223001
3. Hara, M., et al.: Microwave oscillator using piezoelectric thin-film resonator aiming for ultraminiaturization of atomic clock. *Rev. Sci. Instrum.* **89**(10), 105002 (2018). https://doi.org/10.1063/1.5048633
4. Lutwak, R.: Principles of atomic clocks. In: Tutorial Material of the IEEE Frequency Control Symposium. San Francisco (2011).
5. Hara, M., et al.: Injection locking type 1/2 frequency divider employing piezoelectric MEMS resonator for simplifying the micro atomic clock system. In: IEEE 33rd International Conference on Micro Electro Mechanical Systems. Vancouver, pp. 1195–1198 (2020). https://doi.org/10.1109/MEMS46641.2020.9056269
6. Brannon, A., et al.: Self-injection locking of a microwave oscillator by use of four-wave mixing in an atomic vapor. In: IEEE International Frequency Control Symposium Joint with European Frequency and Time Forum. Geneva, pp. 275–278 (2007). https://doi.org/10.1109/FREQ.2007.4319080
7. Hu, J.R., et al.: A 750 \( \mu \text{F} \) 1.575 GHz temperature-stable FBAR-based PLL. In: IEEE Radio Frequency Integrated Circuits Symposium. Boston, MA, pp. 317–320 (2009). https://doi.org/10.1109/RFCIC.2009.5135548
8. Tsubout, M.: A CMOS direct injection-locked oscillator topology as high-frequency low-power frequency divider. In: IEEE Symposium on VLSI Circuits. Honolulu, HI, pp. 132–135 (1998). https://doi.org/10.1109/VLSIC.1998.688031
9. Rategh, H.R., Lee, T.H.: Superharmonic injection locked oscillators as low power frequency dividers. *IEEE J. Solid-State Circuits* **39**(7), 1170–1174 (2004). https://doi.org/10.1109/JSSC.2004.829937
10. O’Donoghue, K., Kennedy, M.P.: A fast and simple implementation of Chua’s oscillator with cubic-like nonlinearity. *Int. J. Bifurcation Chaos* **15**(9), 2959–2971 (2005). https://doi.org/10.1142/S0218127405013800
11. Chua, L.O., Komuro, M., Matsumoto, T.: The double scroll family. *IEEE Trans. Circuits Syst.* **33**(11), 1072–1118 (1986). https://doi.org/10.1109/TCS.1986.1085869
12. Ruby, R., et al.: PCS 1900 MHz duplexer using thin film bulk acoustic resonator (FBARs). *Electron. Lett.* **35**(10), 794–795 (1999). https://doi.org/10.1049/el:19990559
13. Nishihara, T., et al.: High performance and miniature thin film bulk acoustic wave filters for 5 GHz. In: IEEE Ultrasonics Symposium. Munich, pp. 969–972 (2002). https://doi.org/10.1109/ULTSYM.2002.1193557
14. Aigner, R., et al.: Advancement of MEMS into RF-filter applications. In: International Electron Devices Meeting. San Francisco, pp. 897–900 (2002). https://doi.org/10.1109/IEDM.2002.1175981
15. Taniguchi, S., et al.: An air-gap type FBAR filter fabricated using a thin sacrificed layer on a flat substrate. In: IEEE Ultrasonics Symposium. New York, pp. 600–603 (2007). https://doi.org/10.1109/ULTSYM.2007.156
16. Hara, M., et al.: Surface micromachined AlN thin film 2 GHz resonator. *Sens. Actuators, A* **117**(2), 211–216 (2005). https://doi.org/10.1016/j.sna.2004.06.014
17. Ueda, M., et al.: Development of an X-band filter using air-gap-type film bulk acoustic resonator. *Ipn. J. Appl. Phys.* **47**(5S), 4007–4010 (2008). https://doi.org/10.1143/JJAP.47.4007
18. Hara, M., et al.: Super-high-frequency band filters configured with air-gap-type thin-film bulk acoustic resonators. *Jpn. J. Appl. Phys.* **49**(7S), 07HD13 (2010). https://doi.org/10.1143/JJAP.49.07HD13
19. Satoh, H., et al.: A 400-MHz one-chip oscillator using an air-gap type thin film resonator. In: IEEE Ultrasonics Symposium. Denver, CO, pp. 363–368 (1987). https://doi.org/10.1109/ULTSYM.1987.198984
20. Dubois, M.A., et al.: Monolithic above-IC resonator technology for integrated architecture in mobile and wireless communication. *IEEE J. Solid-State Circuits* **41**(1), 7–16 (2006). https://doi.org/10.1109/JSSC.2005.858627
21. Daneshgar, S., De Feo, O., Kennedy, P.: Observation concerning the locking range in a complementary differential LC injection-locked frequency divider-part II: design methodology. *IEEE Trans. Circuits Syst.* **58**(4), 765–776 (2011). https://doi.org/10.1109/TCSIS.2010.2078770
22. Pikovsky, A., Maistrenko, Y.L., Kurths, J.: Synchronization: A Universal Concept in Nonlinear Science. Cambridge University Press, New York (2001)
23. Kirkendall, C.R., Kwon, J.W.: Multistable internal resonance in electrostatic crystals with nonlinearly coupled modes. *Sci. Rep.* **6**, 22897 (2016). https://doi.org/10.1038/srep22897
24. Ivi, B., Kirkendall, C., Lipiainen, L.: Transient response of BAW resonators. In: IEEE International Ultrasonics Symposium. Glasgow, pp. 2188–2193 (2019). https://doi.org/10.1109/ULTSYM.2019.8925810
25. Hara, M., et al.: Drift-free FBAR oscillator using an atomic-resonance-stabilization technique. In: IEEE International Ultrasonics Symposium. Glasgow, pp. 2178–2181 (2019). https://doi.org/10.1109/ULTSYM.2019.8926079