Ultra Low Phase Noise VCXO with Crystal Filter Array

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***Abstract*—This paper demonstrates a 122.88 MHz VCXO module with ultra low phase noise within all frequency adjustment range for 5G infrastructure application. By applying a set of crystal array, the phase noise floor of one-cavity SMD-VCXO could be optimized from (-165) to (-170) dBc/Hz and the phase jitter of VCXO could be reduced from 45 fs to 25 fs . In comparison with TCXO of which output frequency has no significant deviation, the output frequency of VCXO has relatively large change due to its voltage control function. Thus, the central frequency and bandwidth of crystal filter become critical factors in this product. For the product architecture, the 122.88 MHz clock signal is generated from an one-cavity SMD-VCXO and this signal passes through a crystal filter array to improve the phase noise. The crystal filter array consists of at least two crystal resonators in parallel to widen the bandwidth of crystal filter. Finally, the signal would be transform into a specific squire waveform (CMOS, LVDS, LVPECL…) by a buffer amplifier. This technique provide a method to build a platform for optimizing the phase noise and miniaturizing the same grade product size.**

Keywords—VCXO, phase noise, phase jitter, filter

I. Introduction

FIFTH-GENERATION (5G) communications promise to meet consumer demands for multi-gigabit per second wireless speeds by utilizing silicon-based millimeter-wave (mm-wave) systems working. With development of 5G, the related equipment and facilities are built up recently, such as massive mimo (Multi-input Multi-output) and small cell. In order to ensure these transmission qualities, a crystal oscillator with excellent phase noise characteristics is required particularly for the synchronizer circuit of the small cell and remote radio unit (RRU) in the base station due to small error vector magnitude (EVM) request.

In the past few decades, filters such as LC filter [1], transistor circuit filter[2], surface acoustic wave (SAW) filter [3], thin film bulk acoustic resonator filter (FBAR) [3], and crystal filter [4, 5], are used in the timing device as a multiplier to rise up the output frequency [1, 2, 3] and to improve the phase noise of clock signal [4, 5]a. In 2021, W. Hsieh and Y. Chen proposed using at least one crystal filter to optimize the phase noise and G-sensitivity of oscillator [4]. In this article, we further demonstrate a method to use an AT-cut quartz crystals as filter array to build a powerful platform for optimizing the phase noise of VCXO and this platform has potential for miniaturizing the same grade product size.

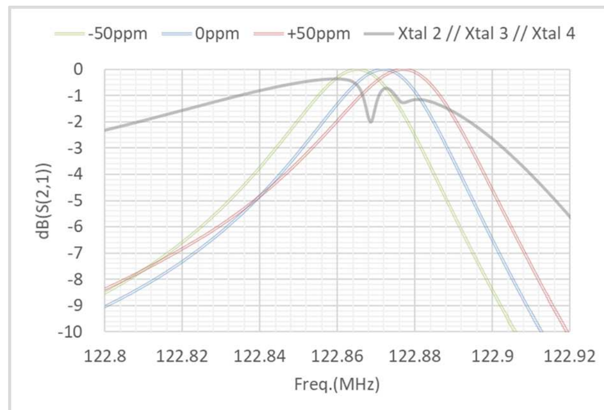

Fig. 1. S_{21} parameter measurement for individual crystals with different resonant frequencies and the filter array with 3 crystals in parallel connection.

II. Design of the VCXO Module

A. Crystal Filter Array

To clarify the bandwidth of the single crystal filter and crystal filter array with three crystals in parallel connection, the practical measurement is implemented. S parameters are used as the index to evaluate the bandwidth. Among the S parameters, S21 indicate the transmission intensity of signal, and the intensity decay (-3dB) is a threshold to judge the bandwidth. Fig. 1 shows the S parameters curve of three individual crystals and the filter array with three crystals in parallel connection measured by a network analyzer (Keysight, E5063A). Based on Fig. 1, the central frequencies of the individual crystal filter shift with the resonant frequency and the bandwidth with respect to -3dB intensity decay is about ± 100 to ±150 ppm. A widened bandwidth of the filter array is indeed observed in practical measurement. However, there is an intensity deviation on the S parameter curve in the pass band range. This could result from the resonance between three individual crystals in parallel.

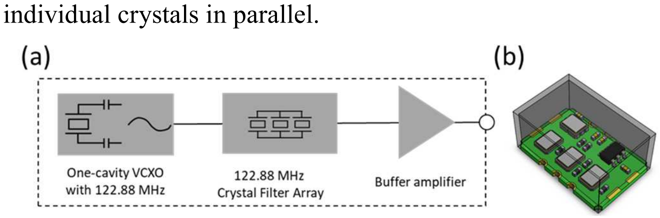

Fig. 2. (a) Block diagram of VCXO module. (b) Perspective drawing of VCXO module.

B. *Circuit of this VCXO*

The block diagram of the VCXO module is shown in Fig. 2(a), which consists of a one-cavity SMD-VCXO, crystal filter array and buffer amplifier. These components are assemble on a 14 × 9.0 mm PCB by surface mount technology (SMT), as shown in Fig. 2(b). The one-cavity SMD-VCXO with a 122.88 MHz fundamental crystal generates a clock signal passing through the crystal filter array. The phase noise of this signal is further optimized by the filter array. Sequentially, the waveform of this signal is modified by the buffer amplifier to become a specific square wave, such as CMOS, LVPECL and LVDS for back end IC application. In addition, the module size could be further shrunk by choosing the smaller components to adapt to the limitation of back-end substrate.

III. PERFORMANCE OF THIS VCXO MODULE

A. *Frequency Characteristics*

The frequency adjustment range of this VCXO module is about ±40 ppm within control voltage from 0 V to 3.3 V and the frequency stability over temperature (-40~85℃) is about ±20 ppm without frequency drift. Thus, the absolute pulling range (APR) is at least ±5 ppm.

B. *Phase noise & Jitter Characteristics*

To verify the optimization of phase noise by crystal filter, the phase noise of a one-cavity SMD-VCXO and this VCXO module are measured. The result shows that the noise floor is certainly improved and the phase jitter reduce from 43 fs to 20 fs, as shown in Fig. 3.

After verification for optimization of phase noise by crystal filter, we further test the filter design how to affect the improvement of phase noise. The VCXO modules with only single crystal filter and a set of crystal array (three crystals in parallel connection) are used in the phase noise measurement. The results show that the phase noise of the VCXO module with only single crystal filter degrades under control voltage 3.3 v, as shown in Fig. 4. At this moment, the output frequency of the one-cavity VCXO is about 122.88 MHz+ 40 ppm, which could be out of the bandwidth of single crystal filter. This results in the noise floor rising up. In contrast with the VCXO modules with only single crystal filter, the module with a set of crystal array shows the excellent phase noise performance within all control voltage range from low to high pulling, as shown in Fig. 5.

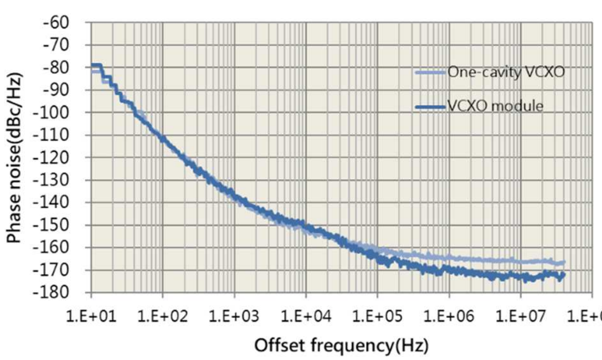

Fig. 3. Phase noise comparison between one-cavity VCXO and VCXO module.

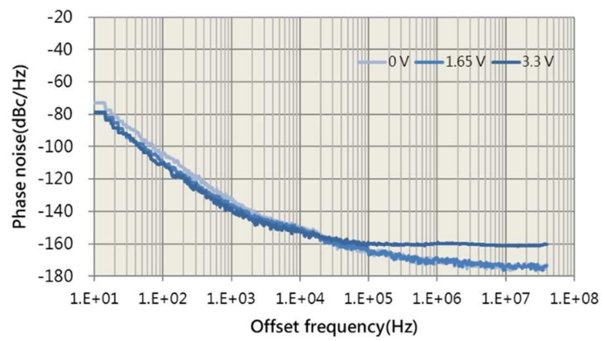

Fig. 4. Phase noise of VCXO module with single crystal filter at control voltage from 0 V to 3.3 V.

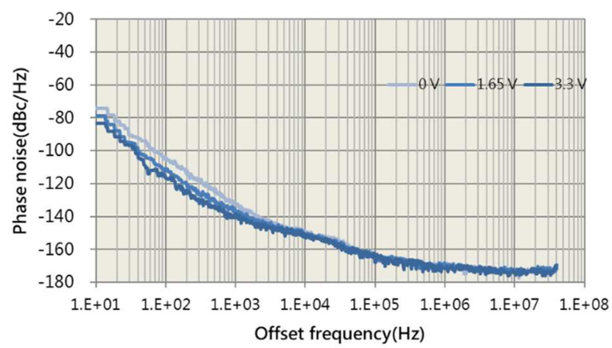

Fig. 5. Phase noise of VCXO module with crystal filter array at control voltage from 0 V to 3.3 V.

IV. CONCLUSIONS

In this paper, we demonstrate a 122.88 MHz VCXO module with an ultra low phase noise performance in all frequency adjustment range. To deal with the relatively large output frequency range of VCXO, a set of crystal filter array with three crystals in parallel connection, which expected to have a wider bandwidth in this VCXO module. To evaluate the bandwidth of filters, the S parameters of a single crystal and a set of crystal filter array are verified by practical measurement. The crystal array indeed shows a widen bandwidth in respect to the single crystal. This technique provide a method to build a platform for optimizing the phase noise and miniaturizing the same grade product size. With better phase noise performance, the proposed ultra-low phase noise VCXO provides more robust alternative for 5G applications.

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