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High-precision frequency synthesizer for geophysical and biotechnical measurements using laser meter

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Abstract. The paper describes a frequency synthesizer for expanding applications and improving the accuracy of a laser device for measuring ultra-small displacements. Such devices are used to measure Earth's crust deformations. The specified device allows measuring the increment of lengths based on 25 m in two mutually orthogonal directions. Year-round use of such device in an observatory tunnel inside a mountain, such as, for example, in the Talaya Observatory near Lake Baikal, allows for detailed recording of Earth's crust deformations by studying the long-term and relatively short-term components of these vibrations. The main use of these results consists in registering a nonstandard change in the deformations, which can serve as a precursor of earthquakes, which causes the highest relevance of these studies. The device contains two lasers tied to each other in frequency with a frequency difference defined from the outside. The binding is carried out by a phase locked loop system, and a reference sample oscillator forms the external frequency. For some applications, the highest accuracy of the frequency tuning of the reference oscillator is required, which is achieved only by using a frequency synthesizer specially designed for this purpose. The paper describes the main circuit solutions for this synthesizer and the results of its use as part of the specified high-precision laser gauge of displacements and deformations of Earth's crust.

1. Introduction

Continuous recording of Earth's crust deformations serves to identify earthquake precursors and is also used to study processes in the earth's crust [1–7]. Such registration can be carried out most efficiently with the help of laser displacement meters, in which a reference arm (length standard) is used or registration is performed using a difference signal in two orthogonal directions to eliminate the effects of atmospheric changes [5–10]. The device, developed by the team of the Institute of Laser Physics of the Siberian Branch of the Russian Academy of Sciences, uses both of these methods to increase accuracy [11–15]. This device has been developed and constructed in several modifications. Several devices are long-term operated in the regions of greatest interest for year-round seismic observations, namely: near Lake Baikal, in Kazakhstan, in the region of Altai Mountains.

A simplified optical design of the device is shown in Fig. 1. The device has a laser source, an interferometer, two corner reflectors and four photo detectors for receiving radiation from the corner

reflectors. Each corner reflector is attached to the rock, and each photo detector receives a mixture of two beams of radiation in such a way that a differential frequency is formed on it. Changes in the phase of these difference frequency signals carry information on changes in the optical lengths of the respective laser beams. Measurement of these phase increments relative to the reference oscillator allows continuous measurement of changes in the distances of interest in real time as continuous functions of time.
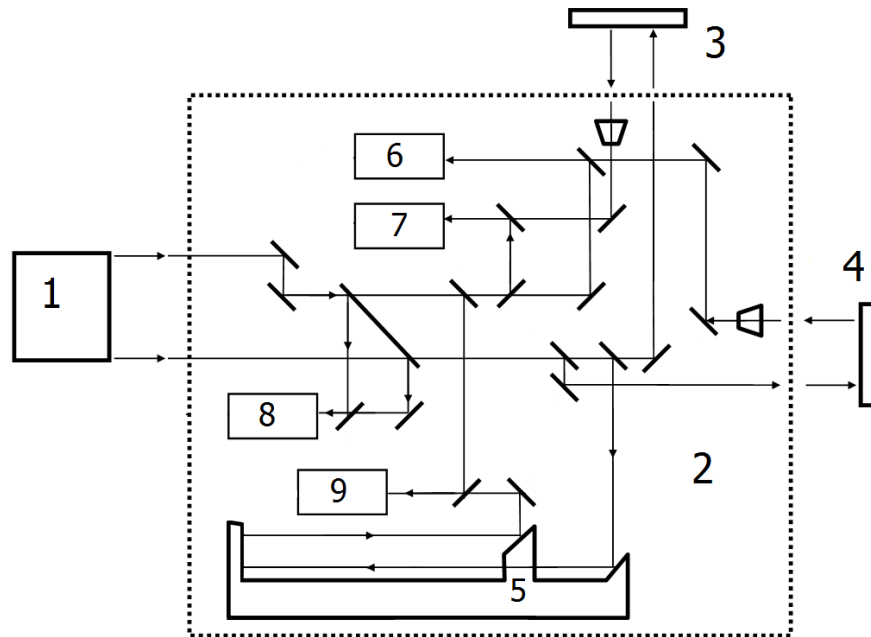

Figure 1. Optical scheme of the interferometer meter of ultra-small displacements: 1 – laser unit; 2 – interferometer; 3, 4 – corner reflectors; 5 – standard of length; 6–9 – photo detectors: arrows show the course of laser beams, slanting lines show mirrors

The laser unit contains two lasers emitting monochromatic (single-frequency) beams of light, while the frequency difference of these beams is stabilized with high accuracy using a phase-locked loop, which binds the frequency of the slave laser to the frequency of the master laser with the desired frequency difference to the phase.

The change of this frequency allows tuning the second laser in frequency relative to the first with high accuracy. This expands the range of applications of the meter and improves its accuracy. The tuning should be made without amplitude and phase jumps, the generated signal should be close to the harmonic signal in form, and its frequency shaping accuracy should correspond to the accuracy of the reference sample frequency generation specified by the quartz oscillator. The acquisition of such a generator is impossible due to the absence of such devices in the market of electronic devices. Therefore, the development and creation of such a synthesizer was required. For the best and most universal functional opportunities for autonomous channels of the synthesizer are required.

This paper describes the technical solutions for creating a frequency synthesizer and the results of its application.

2. Development of a Four-Channel Frequency Synthesizer Based on DDS Technology

The synthesizer is designed to generate four sinusoidal signals physically tied to one master reference quartz oscillator. The ratios of frequencies, phases and amplitudes of all four channels are set in digital form with high accuracy and can be stored in the device's memory for autonomous operation;

the loading of predetermined parameters of the autonomous mode is performed each time it is next turned on. All operations for controlling the synthesizer are carried out from a personal computer via a USB interface. Software for the control computer in conjunction with the software of the microcontroller allows implementing in a wide range of functions of the synthesizer.

3. Technical description of the synthesizer model

The synthesizer is built on the basis of an integrated circuit of a four-channel direct digital synthesis type synthesizer with a speed of 500 MSPS and 10-bit DACs [16]. The AD9959 chip can provide modulation of frequency, phase, or amplitude (FSK, PSK, ASK) with up to 16 discrete levels. The modulation is performed by applying control signals to the profile pins. In addition, the AD9959 supports automatic linear ramping of frequency, phase, or amplitude. This feature may be useful in areas such as radiolocation or measurement technology.

Figure 2 shows a block diagram of the AD9959 DDS synthesizer.

The AD9959 chip consists of four direct digital synthesizer (DDS) cores, which provide independent control of the frequency, phase and amplitude of each channel. Such flexibility can be used to correct the imbalance between signals introduced by analog processing circuits (filters, amplifying circuits), or mismatches related to the topology of the printed circuit board. Since all channels operate on the same system clock signal, they are inherently synchronous. The chip also supports the ability to synchronize multiple crystals.

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The AD9959 serial I/O-port can operate in multiple configurations, providing increased flexibility. The port has an SPI compatibility mode, in which it operates virtually identical to the SPI ports of Analog Devices earlier DDS. Flexibility is provided by four data pins (SDIO_0 / SDIO_1 / SDIO_2 / SDIO_3), which allow selecting one of the four programmable modes of the serial I/O-port.

The AD9959 uses advanced DDS technology that provides low power dissipation while maintaining high quality and performance. The component integrates four high-speed 10-bit DACs with excellent narrowband and wideband SFDR. Each channel has its own phase battery with a 32-bit frequency setting word, a phase shift adjustment of 14 bits and a scaling multiplier at the output of 10 bits depth.

As the reference voltage for the DAC output stage, the supply voltage is used, and the DAC output must be connected to the ADVV via a resistor or to a transformer whose central outlet is connected to AVDD. Each DAC also has its own programmable reference voltage source, which allows working with other values of the full scale current.

DDS works as high-resolution frequency divider, whose input is a REFCLK signal, and the output signal is converted to analog form using a DAC. The REFCLK input signal is common to the two channels and can be fed to the DDS directly or used in combination with the integrated frequency multiplier REFCLK (PLL), which increases the frequency of the reference signal to 500 *MHz*. The multiplier of the PLL is an integer and is programmable in the range from 4 to 20. The REFCLK input stage also contains a generator circuit allowing the use of an external crystal oscillator as the source of the REFCLK. The frequency of the quartz resonator should belong to the range from 20 MHz to 30 MHz. Quartz resonator can be used in combination with the frequency multiplier REFCLK.

The AD9959 comes in a compact 56-pins LFCSP package. The DDS core is powered by 1.8 V supply voltage (AVDD and DVDD pins). The digital input/output interface (SPI) operates at a voltage of 3.3 V and requires connecting the DVDD_I / O pin (i.e. pin 49) to a voltage of 3.3 V. The AD9959 operates in the industrial temperature range from –40°C to + 85°C.
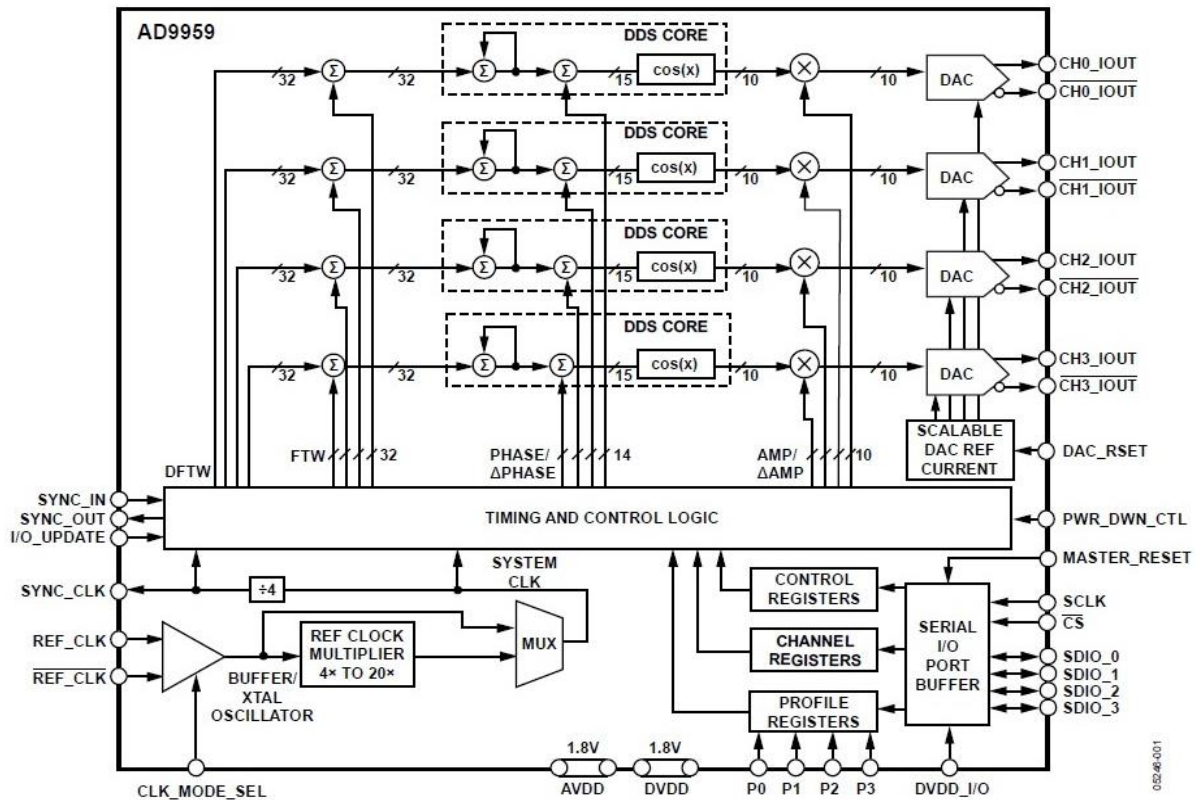
Figure 2. Block diagram of the DDS synthesizer AD9959

Features and advantages of the proposed technical solution are the following ones.
- Four synchronized DDS channels with 500 MSPS speed.
- Independent frequency / phase / amplitude control in individual channels.
- Matched delays when changing frequency / phase / amplitude.
- Excellent inter-channel isolation.
- Ability to scan in frequency.
- Up to 16 modulation levels (modulation is controlled by external pins).
- Programmable current full scale DAC.

The applications fields of frequency synthesizer are the following.
- Fast heterodyne frequency synthesis.
- Phased antenna arrays in radar and sonar.
- Measuring equipment.
- Synchronized clocking.
- RF signal sources for acousto-optic tunable filters.

4. The work of the synthesizer in the laser displacement meter
The electronic layout of the synthesizer layout consists of the following nodes:
- D99 frequency synthesizer AD9959;
- ATmega 128 microcontroller;
- Additional FLASH memory AT45DB041D;
- reference crystal oscillator;
- USB interface;
- four broadband high-frequency amplifiers, containing: 8th order low-pass filters and high-voltage

transformer galvanic isolation;
* stabilizers of secondary supply voltages.

The functional block diagram of the layout of the synthesizer is presented in Fig. 3

The AD9959 DDS chip provides all the basic functions of a synthesizer. The microcontroller controls the operation of the DDS synthesizer chip, ensures the preservation of information for autonomous operation and the updating of information when controlled from an external computer. To work offline and make quick signal changes, the board has an additional FLASH memory. The crystal oscillator generates a highly stable low-noise reference signal with a frequency of 25 *MHz*, which is multiplied by 20 inside the chip of the AD9959 synthesizer, and from which all output signals are then generated. Communication with a computer is carried out via USB interface and provides control of the synthesizer parameters.
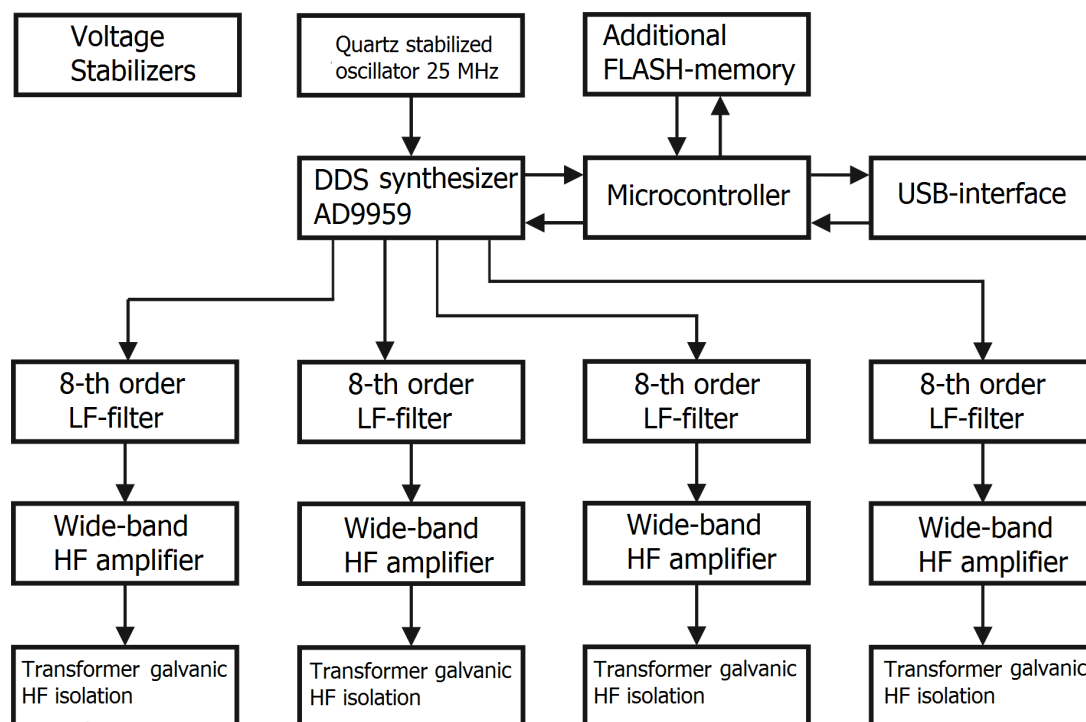

Figure 3. Functional block diagram of the synthesizer layout

The electronic node of the secondary supply voltage source provides all active elements of the board with the necessary supply voltages –3.3 V, 6.6 V and 12 V. The source consists of three pulse DC/DC-converters from TRACO. The input power of DC voltage supply is 24 V.

When the power is turned on, the electronic circuitry forms the initial setup of the microcontroller. Next, the microcontroller begins to control the operation of electronic components of the synthesizer. In this case, signals are generated to control the AD9959 chip, an additional FLASH memory, and computer interaction signals (if connected).

The AD9959 DDS chip generates four pairs of differential output high-frequency signals, each of which is set in frequency, phase and amplitude of the output signal by commands from the microcontroller.

The output signals from the synthesizer chip come to high-frequency amplifiers. Amplifiers contain eighth-order low-pass filters that provide suppression of spurious frequencies. Amplifiers provide a high-frequency signal at the synthesizer output with amplitude of 1 V at a load of 50 Ohm

All four output signals from the synthesizer have galvanic isolation based on RF transformers. The isolation takes place both between the signals and from the rest of the electronic circuit.

5. The Operation of the Synthesizer Controlling Program

Figure 4 presents a block diagram of the control synthesizer.

When operator starts the program "4-channel synthesizer", it begins the search for synthesizer devices connected to this PC. If it is not found, it initiates periodic survey of the operating system for the presence of suitable equipment.
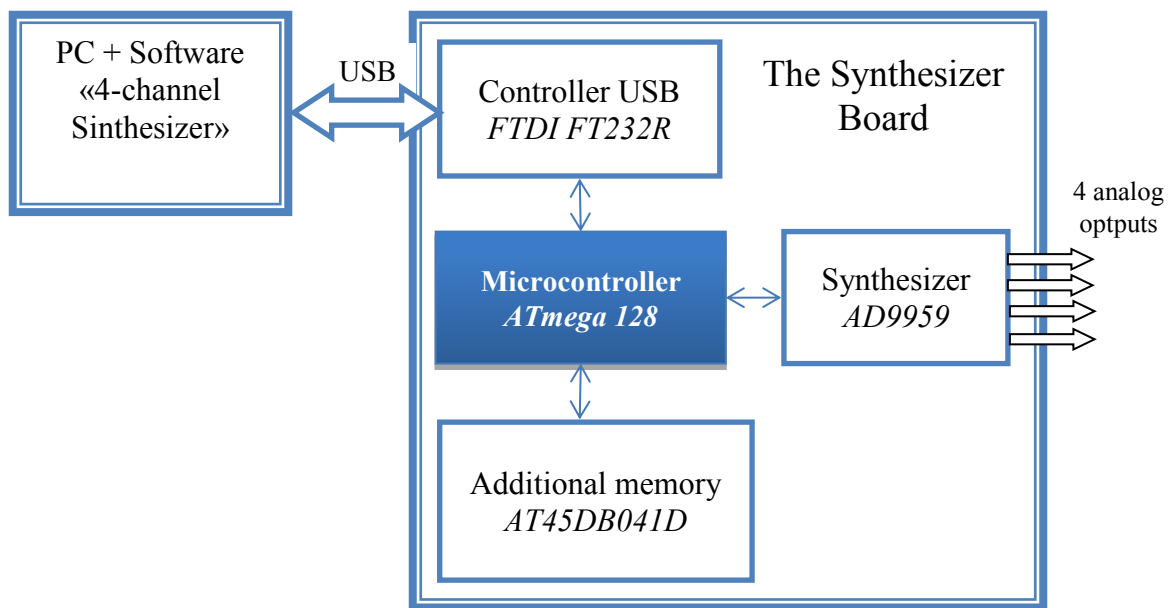

Figure 4. Diagram of the circuit for control of the synthesizer

After detecting the synthesizer board, the program establishes a connection with it and reads from the additional memory of the synthesizer board the values of all parameters for the *State1 - State3* states. At the same time, the current values are set to the *State1* values. The concept of state includes all the numerical parameters visible in the program window, but not the modes of operation.

An operator can change the state of one to the other in the *States* menu. To save the current state values or load the initial values, he can use the *Save* states and *Load states* items, respectively, he can find them in the *Options* menu. When turned on, the synthesizer starts to work in safe mode *Safe mode*. This mode sets on each channel harmonic signals without modulation, the values of the characteristics of which are stored in a separate area of the additional memory of the synthesizer board. While the mode is active, the AD9959 chip registers regularly check the registers for the case of a working error. Exit from the mode and the transition to manual control occurs during the connection of the program "4-channel synthesizer" to the synthesizer board. Setting the values of harmonic characteristics for this mode is done by selecting the item *Fix safe mode* in the *Options* menu. In this case, the current program values will be recorded in the memory, which will be played each time the synthesizer board is turned on.

6. The Main Technical Characteristics of the Synthesizer

The described four-channel frequency synthesizer has the following technical characteristics.

1. Output frequency band from 20 kHz to 150 MHz (1 V amplitude at 50 Ohm load) - 2 channels.

2. Output frequency band from 0.5 MHz to 150 MHz (amplitude 1 V at a load of 50 Ohm) - 2 channels.
3. Step of the frequency change – 0.12 Hz.
4. Phase setting resolution – 14 bits.
5. Amplitude resolution – 10 bits.
6. The frequency of the reference quatz oscillator is 25 MHz.
7. Control parameters of the synthesizer – via USB interface.
8. Independent control of 4-channel output signal parameters.
9. Ability to work offline on the recorded program.
10. Galvanic isolation of high-frequency synthesizer outputs.
11. Output high-frequency connectors type – SMA.
12. Input power supply – 24 V.
13. Power consumption in static mode ~ 4 W.
14. Dimensions of electronic synthesizer board – 82 mm × 185 mm.
15. The dimensions of the electronic board of the power source are 135 mm × 185 mm.

7. The Advantages of Using of the Synthesizer in a Laser Displacement Meter

When using the developed synthesizer, it is possible to control the frequency difference between the radiations of two lasers with a control step equal to 0.12 Hz. This allows us to transfer the spectrum of the differential signal to an arbitrary carrier frequency. In this case, there is an additional opportunity to spread the spectrum of the signal and the spectrum of possible interference that may occur under specific measurement conditions. In addition, such an option allows the system to be configured with high precision, to investigate its accuracy at different carrier frequencies, which makes it possible to more effectively select the carrier frequency for the final realization of the device before its long-term operation.

Conclusion

The developed synthesizer has been successfully tested and implemented in several laser measuring devices operating in various technically difficult conditions. Experimental operation of the synthesizer confirmed its declared technical characteristics and high reliability, which was also ensured due to relatively low consumption and the use of a fully digital element base, which, in turn, allows it to be performed in a sealed design. This is extremely important for operation in humid rooms, such as, for example, mountain tunnel of an underground observatory.

In addition, the described synthesizer can be used to record the speed of turbid media, for example, to measure the speed of water. In this case, the moving water introduces the Doppler frequency shift into the scattered or passing through its signal. Since the moving speed is constantly changing, for a better signal-to-noise ratio, it is necessary to rebuild the filters through which the signal passes before measuring its frequency, but such restructuring is complex and inefficient. It is much more convenient to rearrange the difference frequency so that the signal from the measured liquid remains on the same carrier frequency. In this case, no adjustment of the filters is required; instead, the frequency of the laser radiation is changed. The advantage of this solution is that the photo detectors also do not change their mode of operation, which is much more important when receiving weak high-frequency optical signals.

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