33rd European Modeling & Simulation Symposium
18th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0029 ISBN 978-88-85741-57-7 © 2021 The Authors.
doi: 10.46354/i3m.2021.emss.053

Devising a microwave-photonics frequency synthesizer for prospective radar and communication application

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Abstract

In order to satisfy the requirements for promising communication and radar systems a new concept to design a multi-octave radio frequency (RF) synthesizer that is one of the crucial radio engineering means in demand, is proposed and discussed. In general, the concept is related to the application of the microwave photonics technique to realize the signal processing in super wideband optical range. Using this technique, the approach is referred to intermediate optical signal processing based on optical frequency comb including two optical recirculation loops that operate in the opposite directions of the frequency domain and narrow-band spectral demultiplexers for the needed frequency selection. To verify the concept possibility and efficiency, Cadence AWRDE simulation of RF synthesizer in C-to-W IEEE RF bands with a tuning interval of 4.25 GHz was successfully carried out. In the result, the microwave photonics-based RF synthesizer has been developed is able to operate in the band of more than 4 octaves with approximately the same output power of 4-5 dBm and the higher harmonics' suppression of more than 30 dB.

Keywords: Super wideband communication and radar systems; microwave-photonics technology; millimeter-wave frequency synthesizer; modeling in AWRDE environment

1. Introduction

Modern microwave telecommunication and radar systems are actively mastering the millimeter wavelength range. The most prominent examples in these industries are cellular telecommunication systems of the fifth and subsequent generations [Andrews, 2014; Boccardi, 2014; Effenberger 2019; Rappaport, 2013] and multi-function radars of civil or military applications including non-cooperative target recognition, counters to air-defense threats, and the investigation of the nature of clouds [Skolnik 2002]. In this regard, the use of hybrid technologies for designing individual devices and modules of the corresponding systems, including microwave-photonics technologies, is coming to the first plane. Among other needs, an important task is to develop compact, super wideband, and energy-efficient radio frequency (RF) synthesizers as a common grid for microwave (MW) and millimeter-wave (MMW) reference frequencies.

One of the most promising way to meet the above requirements is considered to devise a synthesizing circuitry based on fairly mature microwave-photonics (MWP) technology [Capmany, 2007; Seeds (2006)], which is currently used worldwide for the development of various millimeter-wave radio devices because implementation of it will enhance the key technical and economical features and such important characteristics as electromagnetic and environmental compatibilities, immunity to external interferences.

Nevertheless, in the process of design, a developer of new MWP-based radio electronic devices (RED) is facing a problem of choosing an appropriate computer-aided design (CAD) tool. For today, the existing optoelectronic CAD tools (OE-CAD) based on so-called Photonic Design Automation (PDA) platform are not developed like being perfected for near five decades CAD tools intended for modeling of RF and microwave circuits (MW-CAD) based on so-called Electronic Design Automation (EDA) platform. To solve the problem of successful introducing MWP technique to the next-generation REDs, our team for almost 10 years has been developing an optimal approach for computer-aided design of MWP-based RED [Belkin, 2016, 2018]. As a result, a set of models for optical, optoelectronics, and MWP devices are presented and validated in the established EDA environment such as Cadence AWRDE [Belkin, 2019, 2020].

Elaborating the approach, in this paper a new concept to design multi-octave MW-to-MMW synthesizer using MWP technology is proposed and discussed. To verify the concept possibility and efficiency, we will simulate RF synthesizer tuning from 4.25 GHz to almost 100 GHz with the interval of 4.25 GHz by Cadence AWRDE CAD tool. In particular, Section 2 of the paper reviews state of the art for RF synthesizers based on a purely electronic approach. The proposed MWP concept and the block-diagram of the MWP-based RF synthesizer are described in detail in Section 3. Sections 4 and 5 discuss the AWRDE models of the synthesizer under study and the modeling results obtained. Section 6 concludes the paper.

2. State of the art

According to the Wikipedia definition, a RF synthesizer (RFS) is an electronic circuit that generates a range of frequencies from a single reference frequency. Today, RFSs are used in many modern RF devices, in particular, radio receivers, mobile telephones, satellite receivers, GPS systems, and so on. The available RFS may use the techniques of frequency multiplication, frequency division, direct digital synthesis, frequency mixing, and phase-locked loops to generate its frequencies. In the most cases, RFSs exploit stable and accurate reference generator, such as a crystal oscillator and subsequent frequency multiplying circuits. Table 1 lists the examples of modern MW and MMW RFSs.

Table 1. Modern MW and MMW synthesizers.

Model	Producer	Parameter	Value
ADF41020	Analog Devices	Input reference frequency	0.4GHz
		Output frequency range	4-18GHz
		2nd harmonic	-
ADF41513	Analog Devices	Input reference frequency	0.8GHz
		Output frequency range	1-26.5GHz
		2nd harmonic	-
PE11S3903	Pasternack	Input reference frequency	50MHz
		Output frequency range	10-20GHz
		2nd harmonic	-15dBc
SLS2 SERIES	L3Harris	Input reference frequency	10MHz
		Output frequency range	0.01-20GHz*
		2nd harmonic	-15dBc
LMX2820	Texas Instrument	Input reference frequency	5-250MHz
		Output frequency range	0.045-22.6GHz
		2nd harmonic	-20dBc
958A/31.5	MI-WAVE	Input reference frequency	10MHz
		Output frequency range	30-33GHz
		2nd harmonic	-20dBc
958W/93.5	MI-WAVE	Input reference frequency	10MHz
		Output frequency range	92-95GHz
		2nd harmonic	-20dBc

* Includes a large number of narrow-band versions

The following outcomes can be drawn from the Table.
1) Currently, a large number of world-famous companies operate on the RF synthesizer market.
2) All existing RF synthesizers are designed on the basis of a purely electronic approach and can be divided into two classes: either multi-octave ones operating up to IEEE K-band (up to a maximum of 26.5 GHz), or single-octave ones operating in IEEE K_a- or W-band (up to 97 GHz).
3) All models, in spite of the special measures taken, have a relatively low purity of the output spectrum with suppression of the 2nd harmonic within 15-20 dB.

Thus, in order to satisfy the requirements for promising communication and radar systems (see Introduction), a new principle of designing RF synthesizers is needed, which ensures their efficient multi-octave operation simultaneously in MW and MMW spectral bands

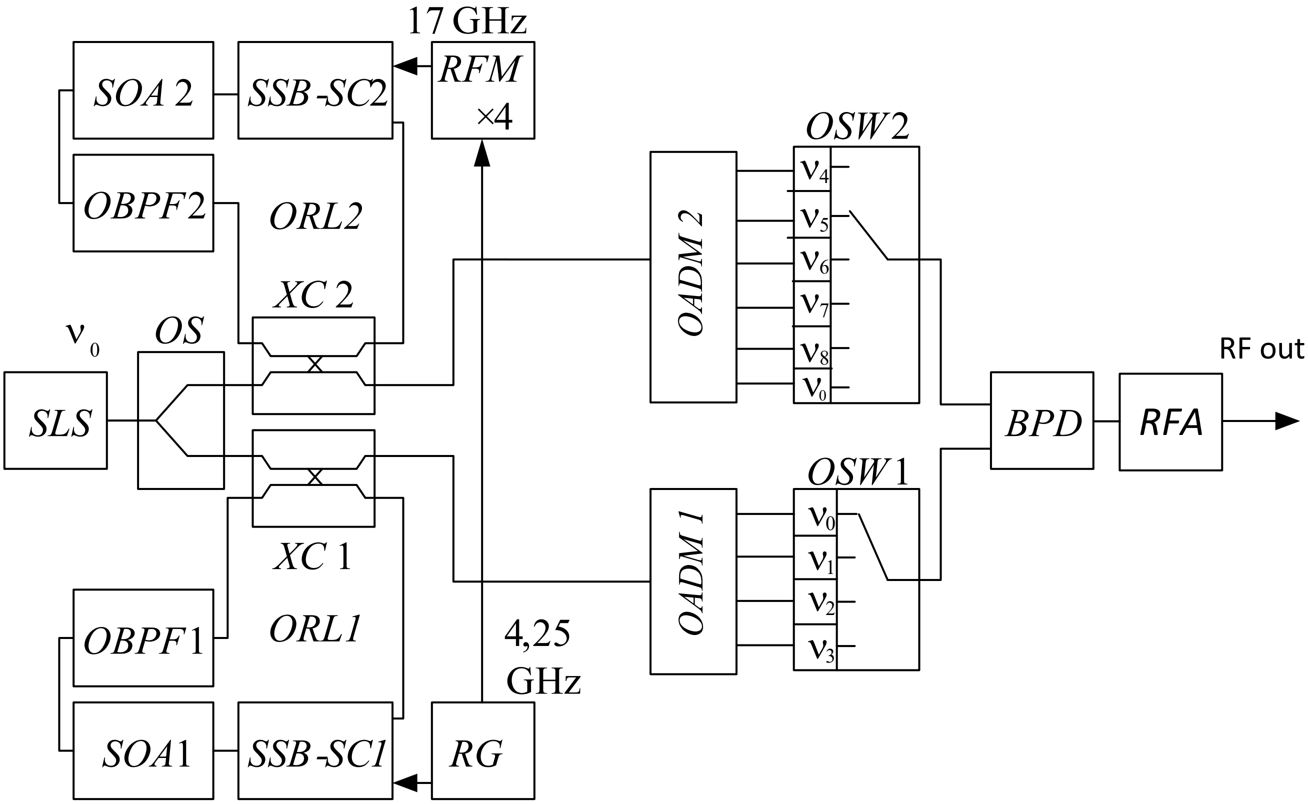


Figure 1. The block-diagram of the MWP-based RF synthesizer

3. The proposed microwave-photonics concept

Figure 1 shows the block-diagram of the MWP-based RF synthesizer has been proposed. In general, the proposed RFS consists of 4 sequential stages: reference generation unit (RGU), electrical-to-optical converting unit (EOCU), optical processing unit (OPU), optical-to-electrical converting unit (OECU). In the block-diagram of Figure 1, the first one includes a main 4.25 GHz reference generator (RG) and an additional 17 GHz RG, which is formed by a 4-order RF multiplier (RFM); the second one includes a semiconductor laser source (SLS) emitting optical frequency ν_0. In addition, the OPU contains 1x2 optical splitter (OS), to each output of which a corresponding optical recirculating loop (ORL1 or ORL2) is connected. The main elements of each ORL are an X-type coupler (XC1 or XC2), an electro-optical single-sideband modulator operating in suppressed carrier mode (SSB-SC1 or SSB-SC2) a semiconductor optical amplifier (SOA1 or SOA2) that compensates for loop losses, and an optical bandpass filter (OBPF1 or OBPF2) that limits the number of recirculations. Note that the output of the lower SSB-SC1 modulator is controlled by a 4.25-GHz RF signal, and the upper SSB-SC2 modulator is controlled by a 17-GHz RF signal. In addition, the optical modulators are tuned in such a way that with each recirculation, the output optical frequency increases or decreases by the value of the modulating signal frequency. Namely, in the block-diagram of Figure 1, the frequency of ORL1 is increased by 4.5 GHz, while the frequency of ORL2 is decreased by 17 GHz.

The optical frequency combs generated in the ORLs are fed to the input of the corresponding optical add/drop multiplexer (OADM1 or OADM2) for sequential selection of each optical frequency. Specifically, with the help of the OADM1, the optical frequencies of ν_0, ν_1, ν_2, ν_3 are selected, while with the help of the OADM2, the optical frequencies of ν_0, ν_4, ν_5, ν_6, ν_7, ν_8 are selected. The output signals of both OADMs are selected using electrically controlled optical switches (OSW1, OSW2) and are suitably combined in the OECU containing a balanced photodetector (BPD) and an RF amplifier (RFA).

4. Modeling Experiment

In general, our proposed behavior principle for designing MWP circuits in a MW-CAD tool [Belkin, 2016] is based on the devising the models of optoelectronic and optical elements in the form of physical equivalent circuits. In the scheme of the RFS under study, using this technique, the models of a SLS, a SSB-SC modulator, and a BPD have already been developed [Belkin, 2018A, 2018B]. Due to the similarity of the fundamental principles of the design platforms, for models of optical passive and active elements (OS, XC, OBPF, SOA, OSW), the similar library models of the computer tool can be used. An OADM1 model based on the library models of RF diplexers, isolators, amplifiers is shown in Figure 2. The model of OADM2 was devised in a similar way.

The generalized model of the MWP-based synthesizer under study compiled in the form of a sub-circuit containing previously published models and the model of Figure 2, is shown in Figure 3.

5. Simulation Results

The first modeling run was intended to determine the optical spectra at the outputs of OADM1 and OADM2. Figure 4 presents the combined optical spectrum obtained as a result of calculations, indicating the frequencies of the optical comb at the output of the OADMs. Note that, according to the accepted operating modes of optical modulators inside ORLs, frequencies of ν_1, ν_2, ν_3 are located above the carrier frequency ν_0, of the SLS with a step of 4.25 GHz, and frequencies ν_4, ν_5, ν_6, ν_7, ν_8 are located below it with a step of 17 GHz.

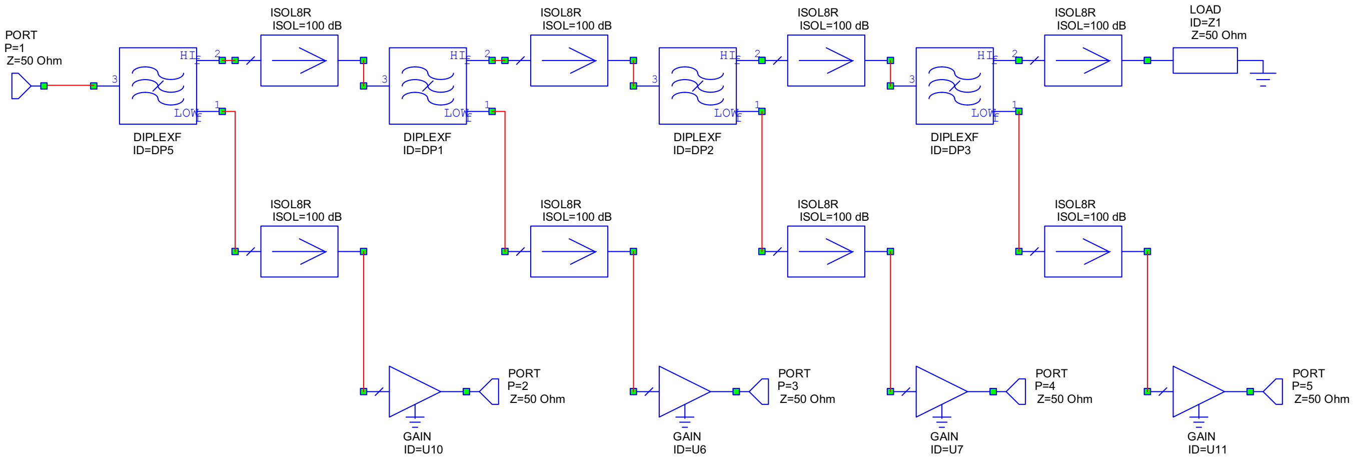


Figure 2. AWRDE model of OADM1

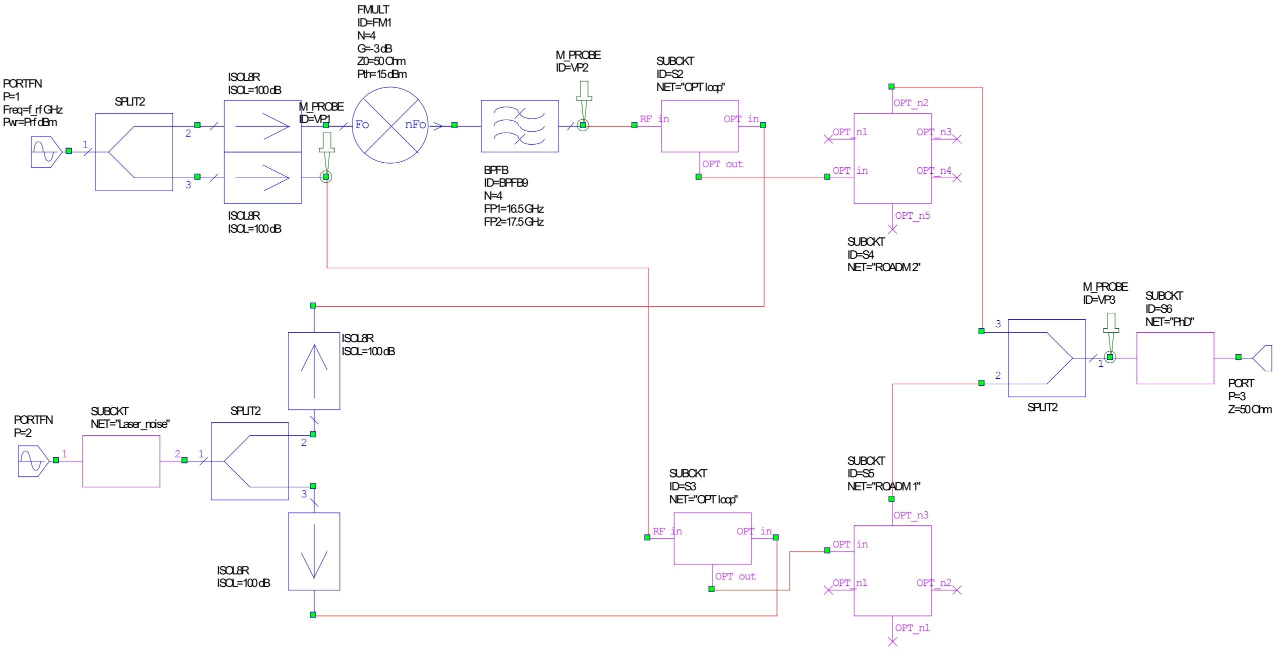


Figure 3. Generalized AWRDE model of the MWP-synthesizer under study

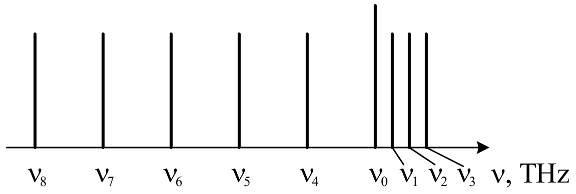
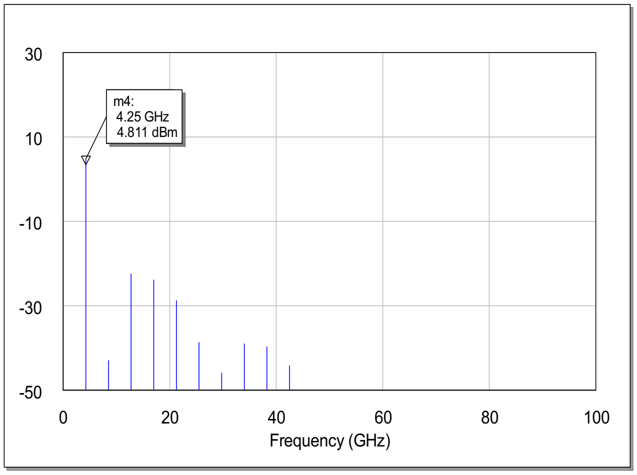
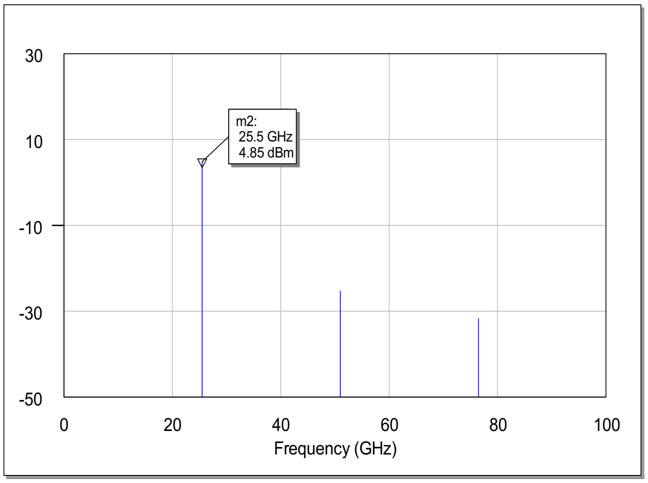


Figure 4. Combined optical spectrum at the output of the OADMs

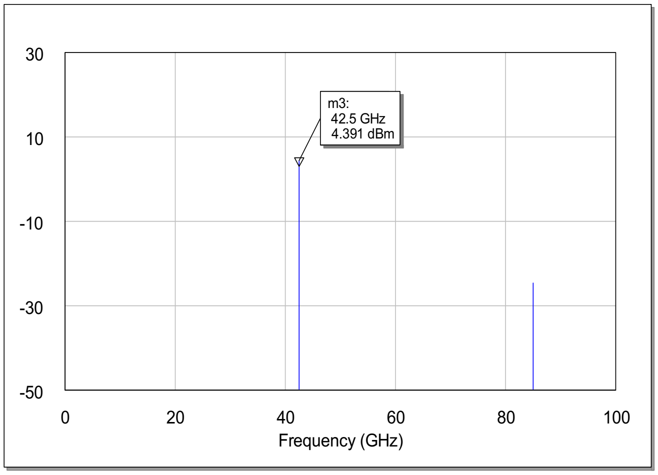
The second run of the simulation using the model of Figure 3 is referred to calculating RF spectra at the output of the MWP synthesizer under study in the recommended RF bands for 5G communication network [WRC-2019]and in a band higher than 71 GHz for the beyond 5G generation. The results of the simulation experiment are shown in Figure 5.



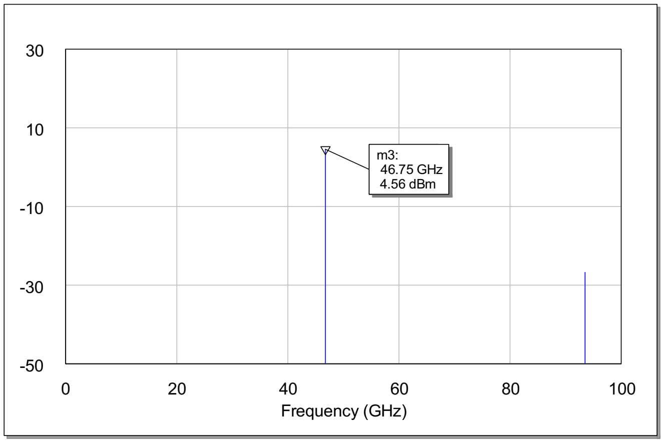
a) In MW range



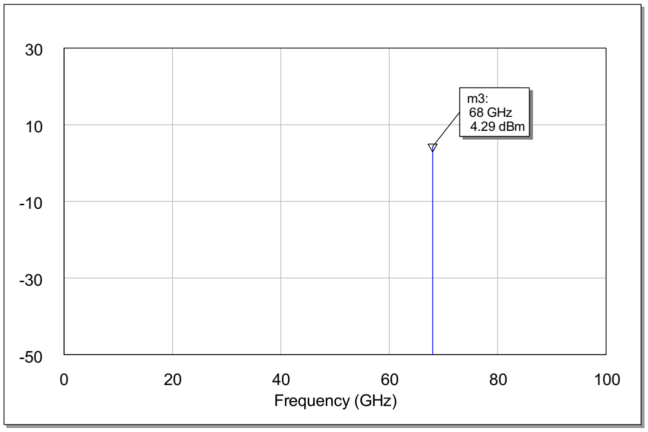
b) In MMW range, band 1(24.25-27.5 GHz)



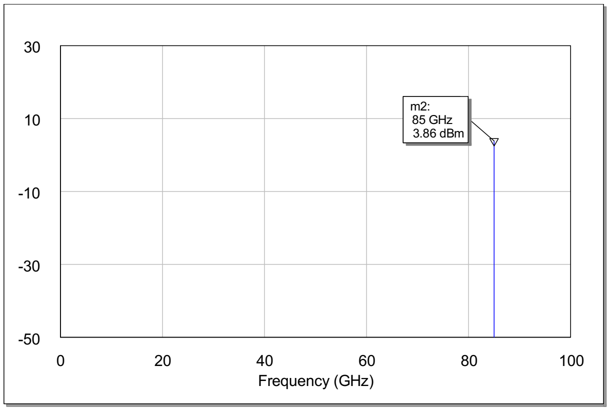
c) In MMW range, band 2 (37-43.5 GHz)



d) In MMW range, band 3 (45.5-47 GHz)



e) In MMW range, band 4 (66-71 GHz)



f) In MMW range: a band for beyond 5G

Figure 5. Exampling spectra at the output of RFS under study

The following outcomes can be drawn from the Figure.

1) The RF synthesizer has been developed due to using MWP technology is able to operate in the band of more than 4 octaves with approximately the same output power of 4-5 dBm.

2) At the same time, in all parts of the RF spectrum, the suppression of higher harmonics of more than 30 dB is provided.

6. Conclusions

In the paper, we proposed and described a new concept to design a multi-octave radio frequency synthesizer using microwave-photonics technology. The approach is particularly suitable for prospective radar and communication applications. The selected solutions are based on the intermediate optical signal processing using optical frequency comb including optical recirculating loops and narrow-band optical add/drop multiplexers. To verify the concept possibility and efficiency, an AWRDE simulation of radio frequency synthesizer in C-to-W IEEE bands with a tuning interval of 4.25 GHz was carried out. In the course of a computer experiment, the feasibility and competitiveness with existing functional analogues of the proposed concept was demonstrated and the parameters of the device under study were confirmed.

Funding

This work was funded by the Russian Foundation for Basic Research, Grant No 18-29-20083.

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