Microwave-Photonics Frequency Up-Converter for Telecom and Measurement Equipment

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Abstract. An ultra-wideband tunable frequency converter scheme for microwave and millimeter-wave signal generation based on optical recirculating loop and microwave-photonics technique, is proposed and demonstrated. The scheme consists of standard, commercially available elements such as dual parallel Mach-Zehnder modulator, optical filter, wideband photodiode and does not require ultra-broadband RF components. A recirculating loop acts as an optical frequency comb generator and allows obtaining multiple local oscillator signals at frequencies that significantly higher than the RF reference used. Up-converted signals of frequencies in mm-wave band are demonstrated experimentally with spectra free of spurious products. The converter proposed could be used as an alternative solution to microwave mixers in telecom and measurement equipment.

1. Introduction
Recent advances in communication and radar technologies drive the growth of demand for test and measurement equipment [1]. As the frequencies overcome Ka-band threshold, the problem of ultra-wideband signal processing becomes more and more challenging [2] and modern radio-frequency (RF) measuring apparatuses are no longer able to meet the requirements [3]. Besides, utilizing license-free mm-wave bands is a possible solution for broadband communication in next generation wireless networks [4]. For example, wide bandwidth available between 60 and 90 GHz enables wireless links with more than 10-Gbps throughput that is significantly higher than at lower RF bands.

Communications at such high frequencies pose unique challenges, one of which is an efficient frequency conversion. A common approach to up- and down-conversion in communication hardware as well as in a measurement equipment relies upon electronic mixers [5]. As the frequencies rise to a sub-THz domain and bandwidth exceeds octave, these mixers become more and more unpractical. Traditional mm-wave frequency conversion networks tend to be narrowband, bulky and costly that prompts us to look for alternative solutions.

A novel microwave photonics (MWP) approach based on electronic-to-optical conversion of RF signals and their optical domain processing has established itself as a promising solution [6]. The basic principle of photonic signal processing is to convert RF signal into optical domain, for example via intensity modulation of light, carry out some operations in optical band, and then demodulate it back into RF. The main idea is that some types of processing are easier to perform in optical domain. This paper presents a novel design concept and key experimental performances of MWP up-converter for telecom and measurement equipment that is proposed for overcoming the above-mention challenges of mm-wave applications.
2. Principle of Operation

Figure 1 shows the schematic diagram of proposed wideband MWP frequency up-converter. The lightwave is emitted from a continuous wave (CW) narrow-linewidth semiconductor laser and being split into two branches by optical coupler (OC). The upper branch contains a dual parallel Mach-Zehnder modulator (DPMZM) for single-sideband suppressed-carrier (SSB-SC) electro-optic modulation (EOM) of lightwave with intermediate frequency (IF) signal. This DPMZM is biased properly to suppress lower sideband of optical spectrum; its output optical field $E(t)$ is described in simplified form by

$$E(t) = E_0 \cos[2\pi(\nu_0 + f_{IF})t],$$

where $E_0$ is an optical field amplitude, $\nu_0$ is a laser frequency and $f_{IF}$ represents IF signal frequency.

DC bias is applied to the DPMZM using so-called modulator bias controller (MBC). It’s primary function is to track for modulator’s transfer function drift and to move modulator’s operating point (bias) in a coordinated manner. Tracking is accomplished by applying low-frequency (kHz-range) pilot tone to the DPMZM and processing response of the monitoring photodiode that is embedded in the modulator.

The lower branch is intended to form a tunable local oscillator (LO) signal and contains an optical recirculating loop (ORL), a wavelength division demultiplexer (DMUX) and N-position electrically controllable optical switch element.

The ORL acts as an optical frequency comb generator. It consists of another SSB-SC modulator, an erbium doped fiber amplifier (EDFA) to compensate for losses in the loop and an optical bandpass filter (OBPF) for optical spectrum conditioning. As the laser signal passes the loop round by round, its spectrum takes the form of a frequency comb with a spacing, equal to the reference frequency $f_{REF}$. ORL operates as follows. DPMZM performs EOM of the reference signal $f_{REF}$ from the RF synthesizer. This modulator is biased to suppress upper sideband of optical spectrum and its output is mathematically represented by equation (1) with a change of sign between $\nu_0$ and $f_{IF}$. After amplification in EDFA, the signal passes through an OBPF that rejects the spectral components outside the operating frequency band.

Note that the comb period can be easily fine-tuned by changing the synthesizer reference frequency. The total number of usable LO frequencies $N$ is given by

$$N = \Delta f_{PD} / \Delta f_{IF},$$

where $\Delta f_{PD}$ is a PD bandwidth and $\Delta f_{IF}$ is the expected bandwidth of IF signal.

The output radio frequency (RF) signal is produced as a result of beating an upper sideband (IF) and a lower sideband (LO) optical signal components at the photodetector (PD). The lower sideband component is selected by simply switching to the proper spectral demultiplexer output that corresponds to the desirable operating RF band. A stable performance over the entire operational range is provided by the flat frequency response of PD.
This circuit is also capable to down-conversion. RF and IF change their places and one of the modulators is reconfigured to provide lower sideband modulation instead of upper sideband. This is done by simply changing a DC control voltage applied to the modulator by MBC, so it is reconfigurable indeed.

SSB modulator in a fiber loop is not the only way to generate frequency comb. Circuits with mode-locked lasers and Fabry-Perot modulators are known [7, 8]. They require complex stabilization mechanisms whereas the circuit proposed produces accurate frequency comb without stabilization because the frequency shift is completely determined by accuracy of RF reference signal.

3. Experimental Results

An experimental investigation of the proposed scheme was implemented following the setup of figure 1. It includes Teraxion PS-LM distributed feedback laser module as a source of light with a frequency of $\nu_0 = 193.317$ THz, iXblue MXIQ-LN-40 DPMZMs in both branches controlled by iXblue MBC-IQ-DG-BT MBCs, Ericsson EDFA, optical switch and couplers from Opneti, and Finisar XPDV3120R 70-GHz photodiode for optical-to-electrical conversion and mixing. To date, commercially available DMUXs are designed for frequency steps of 50 GHz and 100 GHz. So, they are not able to select a separate comb component with a lower step. For this reason, the DMUX in our setup was constructed by the corresponding set of Teraxion’s tunable OBPFs with less than 1-GHz bandwidth.

Figure 2 shows the upper-branch output representing the SSB-SC-modulated IF signal for two IF frequencies using in the experiment. The carrier suppression ratio is more than 30 dB and the lower sideband suppression ratio is about 20 dB. This parameter is determined by the extinction ratio, the branch balance of the modulator and by accuracy of the DC control voltage setting.

Optical frequency comb spectrum at the output of the ORL is shown in figure 3. Comb period is determined by reference frequency, useful LO frequencies are determined by equation (2) and amplitude equality depends on response flatness of the EDFA and the OBPF. Figure 4 exemplifies the OBPF’s output centered at the frequency of $\nu_0 + 34$ GHz (reference doubled). The adjacent optical channels are suppressed by approximately 40 dB. This signal will ultimately beat at the PD to produce an up-converted output, so side channel suppression is important for spectrum purity of the resulting RF signal.

An example of RF spectrum of the PD output measured by Keysight E4448A spectrum analyzer is illustrated in figure 5. The output power falls from -19.5 dBm at 6.5 GHz (a) and 8 GHz (b) to -30 dBm.

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**Figure 2.** Output of the upper branch. $f_{IF} = 6.5$ GHz (left), $f_{IF} = 8$ GHz (right)

**Figure 3.** Output of the optical recirculating loop, $f_{REF} = 17$ GHz.

**Figure 4.** Output of the OBPF, $f_{LO} = 34$ GHz.
at 40.5 GHz (c) and 42 GHz (d). Conversion loss is about 40 dB in reference doubling mode. This low
signal level can be explained by low sensitivity of the applied PD. There is a compromise between PD
bandwidth and sensitivity. High bandwidth leads to low sensitivity. Nevertheless, RF amplification is
mandatory in any case.

Figure 5. RF spectra of the PD output: a) $f_{RF}=6.5$ GHz; b) $f_{RF}=8$ GHz; c) $f_{RF}=40.5$ GHz; d) $f_{RF}=42$ GHz.

What is important is that the spectrum is clear and contains no spurious products, so this RF output
has the potential of practical use. This experiment validates the principal applicability of the proposed
scheme in communication hardware as well as in a measurement equipment when using an appropriate
amplifier.

4. Conclusion

A microwave-photonics-based frequency up-converter scheme is proposed for mm-wave signal
generation. This converter is of relatively simple design, does not require high frequency RF components
and relies upon off-the-shelf commercially available elements. A high quality C-to-V band up-
conversion is realized experimentally through all-optical processing with as low as 17-GHz reference.
During these experiments, we were limited by the photodiode available in our disposal, but the potential
of the scheme itself is bounded only by photodiode bandwidth, and there are already more than 100 GHz
off-the-shelf devices. Thereby photonic frequency conversion is a promising approach in mm-wave
band, despite the relative complexity and technology immaturity. Therefore, we are concentrated today
at applying the proposed scheme for communication link in unlicensed 60-GHz band studying its key
characteristics and quality metrics.

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