146-GHz millimeter-wave radio-over-fiber photonic wireless transmission system

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Abstract: We report the experimental implementation of a wireless transmission system with a 146-GHz carrier frequency which is generated by optical heterodyning the two modes from a monolithically integrated quantum dash dual-DFB source. The monolithic structure of the device and the inherent low noise characteristics of quantum dash gain material allow us to demonstrate the transmission of a 1 Gbps ON-OFF keyed data signal with the two wavelengths in a free-running state at 146-GHz carrier wave frequency. The tuning range of the device fully covers the W-band (75 – 110 GHz) and the F-band (90 – 140 GHz).

OCIS codes: (060.5625) Radio frequency photonics; (040.2840) Heterodyne; (130.0130) Integrated optics.

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1. Introduction

Radio-over-fiber (ROF)-based optical–wireless networks are emerging as an affordable alternative solution in environments where roaming connections are needed, such as conference centers, airports, hotels, and ultimately homes and small offices [1]. These

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solutions require broadband wireless access (BWA) technologies, which are currently constrained by the required bandwidth particularly for video-centric services with high-definition TV (HDTV) quality. This issue can be addressed either using complex modulation formats or using higher carrier frequencies, reaching into the millimeter-wave (mm-wave) bands [2]. There is especial interest in frequencies near 35, 94, 140 and 220 GHz, for which there are atmospheric windows for transmission [3]. However, generating carrier wave frequencies above 100 GHz using electrical devices is challenging due to the limited frequency response of electronic components. An attractive alternative solution is to use optical means [4].

Optical techniques have traditionally been used to generate stable signals over a wide range of frequencies, employing a variety of methods such as direct modulation, external modulation, mode-locking and optical heterodyning. Optical heterodyning, in which a beat signal is generated at the difference frequency between two lasers, has been demonstrated to be the most flexible in terms of frequency, with commercial systems now available that cover from a few GHz up to 2 THz [5]. The main drawback is that the signal purity depends on having highly stable sources or a phase-locking mechanism for the two wavelengths. The advantage of this technique is that it is especially well suited for RoF applications since the beat note is insensitive to dispersion in optical fiber [6].

Distributed feedback (DFB) semiconductor lasers have been commonly employed to produce the two wavelengths needed for heterodyning in a variety of ways. Early research demonstrated that bandwidth restriction of an active DFB section could be used to select two modes in an extended cavity laser structure, concentrating the optical power on those modes and avoiding external filters [7]. Recently, photonic integration has been used to grow monolithically two single-mode DFB lasers which were coupled through a Y-branch section. This device has been shown to generate a low phase noise signal at 42 GHz, an eighth harmonic of the device relaxation oscillation frequency, when a 5 GHz electronic modulation signal is injected [8]. More recently, a gain switched DFB laser at 15 GHz with external optical filters has been demonstrated for the distribution of 60 GHz signals over fiber to remote antenna units (RAU) [9].

Here we report the experimental implementation of a wireless transmission system with a 146 GHz carrier frequency which is generated by optical heterodyning the two modes from a dual-DFB source. For the first time to our knowledge, the two DFB lasers are monolithically integrated on quantum dash material. The monolithic structure of the device and the low noise characteristics of integrated DFB lasers allow us to demonstrate the transmission of a 1 Gbps ON-OFF keyed data signal with the two wavelengths in a free-running state. Our work points to the great potential of photonic integrated circuits to enable the development of wireless systems operating in the millimeter wave range [10].

2. Dual wavelength source

One of the key elements in the reported transmission system is the monolithic dual wavelength source, designed to produce the carrier frequency by optical heterodyning. The device, shown in Fig. 1, has two DFB lasers separated about 20 µm apart to generate the two wavelengths required. These devices have several features that make them suitable for the generation of a high frequency carrier wave:

a) The lasers are grown on InGaAsP in a quantum dash in a well structure with a total of six dash layers. Thanks to a careful design of the Bragg grating and choice of cavity length for each integrated DFB laser the linewidth of each optical tone can be maintained below 1 MHz. Previous studies on these devices report a 3 dB optical linewidth below 900 kHz, with the device used in our setup, with 780 µm length, having an optical linewidth below 700 kHz [11]. Thus, the heterodyne beat note linewidth is expected to be less than twice this figure.

b) Active/passive integration allows monolithic integration of the two sources with passive elements. These are a Y-coupler that combines the two wavelengths from

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each DFB into a single passive waveguide. The integration of the combiner has already been shown effective in reducing the phase noise of the beat note by suppressing the fluctuation of the optical path length difference between the different elements [12]. The output waveguides, at the rear side of each DFB laser as well as the combiner exit waveguide are angled 7° at the facets to reduce reflections.

c) The device presents a wide tuning range of the spacing between the two wavelengths, and therefore of the generated carrier wave frequency.

The separation of the wavelengths of the two DFB devices can be tuned through the DC bias currents, I_{DFB1} and I_{DFB2}. Figure 2 presents the achievable wavelength spacing in the device, as the current I_{DFB1} was varied for different fixed values of I_{DFB2}. As shown, the wavelengths can be spaced from 70 GHz when I_{DFB1} = 200 mA and I_{DFB2} = 100 mA up to 146 GHz when I_{DFB1} = 100 mA and I_{DFB2} = 200 mA, fully covering the W-band (75 – 110 GHz) and the F-band (90 – 140 GHz). The slope of the traces indicates a 0.4 GHz/mA slope. The optical spectra at selected current combinations, which result in increasing wavelength spacing, are presented in Fig. 3. The injected currents, which meet the condition $I_{DFB1} + I_{DFB2}$ = 300 mA, are the current pairs (I_{DFB1}, I_{DFB2}) = (200, 100) (180, 120) (160, 140) (140, 160) (120, 180) and (100, 200) which respectively result in a wavelengths spacing of 76, 87, 100, 115, 129 and 146 GHz. As can be seen, as the wavelength spacing increases, the side mode suppression ratio (SMSR) improves from 28 dB at 76 GHz up to 34 dB at 146 GHz. As the SMSR improves, the difference between the peak powers of the two wavelengths varies in the same amount, measuring a 6 dB difference in the worst case at 146 GHz.

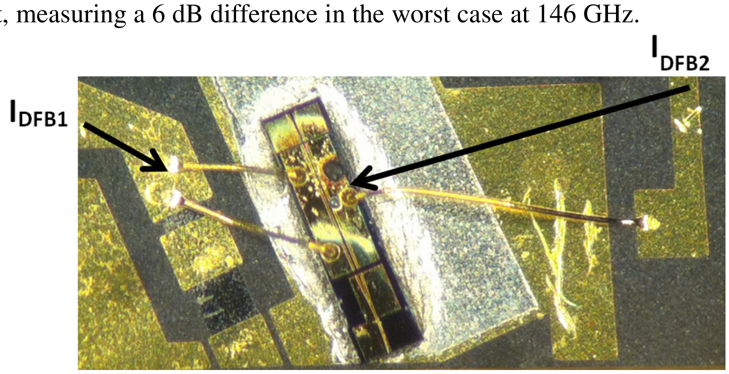

Fig. 1. Picture of the dual wavelength source, composed of two DFB lasers (DFB1 and DFB2) combined through a Y-coupler.

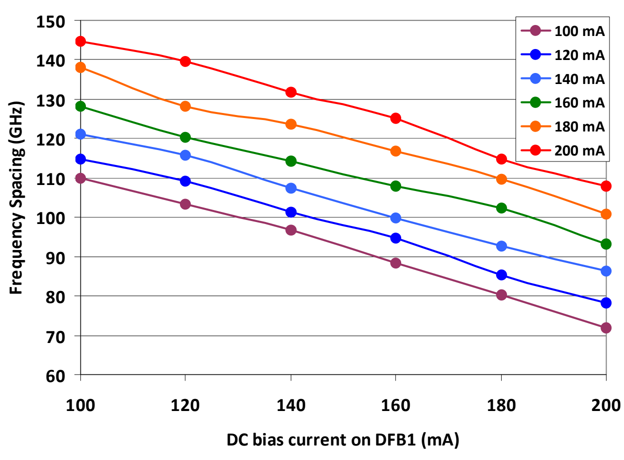

Fig. 2. Dependence of the frequency spacing between DFB1 and DFB2 wavelengths as the DFB1 current is varied at various fixed values of DFB2 current.

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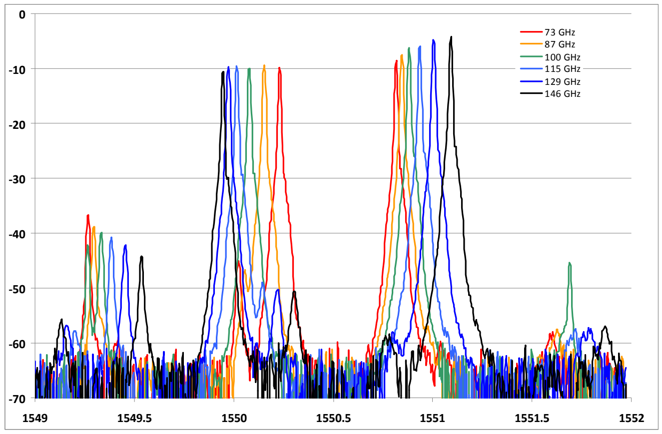

Fig. 3. Optical spectra obtained for various combinations of I_{DFB1} and I_{DFB2} currents generating increasing frequency spacing.

3. Photonic wireless system

Based on the device described in the previous section, we have implemented an optical–wireless transmission system. The schematic layout is presented in Fig. 4. The dual wavelength laser was placed on a thermal controlled stage, and two DC input currents were provided. The two optical modes at the output of the Y-coupler were coupled into a lensed fiber followed by an optical isolator. An erbium-doped fiber amplifier (EDFA) amplified the output signal, which was then modulated with a 1-Gb/s non-return-to-zero (NRZ) on-off keying (OOK) pseudorandom bit sequence (PRBS) data signal of $N = 2^7$-1 bits using a Mach-Zehnder modulator (MZM). The modulated optical signal was amplified by a second EDFA, and then opto-electronically (O/E) converted by means of a packaged high-speed antenna-integrated traveling-wave uni-traveling carrier photodiode (TW-UTC-PD). The TW-UTC-PD was integrated with a broadband log-periodic antenna [13] and packaged with a 6 mm diameter Si-lens to provide a gain of approximately 10 dBi at 146 GHz.

The receiver was a commercially available Schottky diode based subharmonically-pumped mixer (SHM), that down-converts wireless carrier waves within the 140 – 220 GHz band. Given this range, we have worked with a carrier wave frequency at 146-GHz. In conjunction with a 6x frequency multiplier, a low frequency signal generator was used to provide the mixer local oscillator (LO) signal required to achieve a 2.5 GHz intermediate frequency.

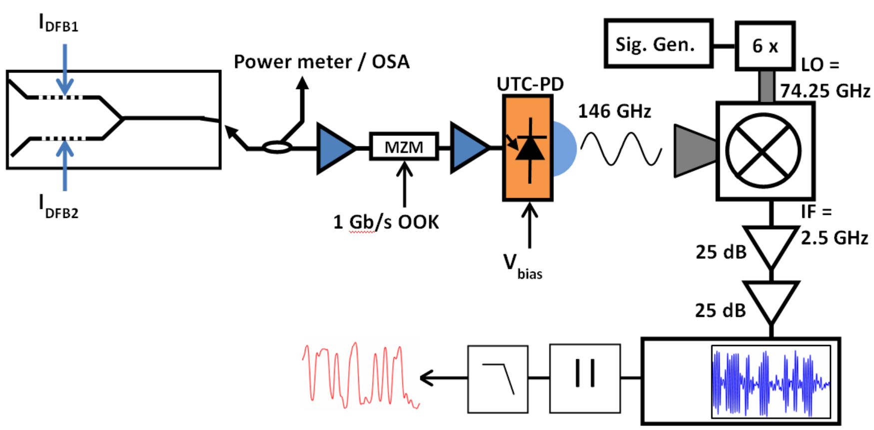

Fig. 4. Schematic diagram for the experimental 146-GHz wireless transmission system.

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3. Results

The dual DFB source was biased at I_{DFB1} = 200 mA and I_{DFB2} = 100 mA, producing a wavelength difference of 146 GHz, within the band of the SHM receiver. The UTC-PD was reverse biased at 2 V and generated 2 mA photocurrent, well below the maximum absolute ratings. The optical power in the PD input fiber was + 13 dBm. Under these conditions, Fig. 5 shows the received IF signal without and with superimposed data. The figure shows that the received IF power is about −10 dBm, including 50 dB gain and 8 dB double sideband conversion losses at the SHM. These values let us estimate a received mm-wave power of around −50 dBm. With a receiver antenna gain of 20 dBi and 2.5 cm distance over the air from transmitter to receiver, we estimate that the UTC-PD generated mm-wave power is around −30 dBm. This signal is observed on a real-time scope and processed off-line to simulate envelope detection to give the baseband eye diagram, shown on Fig. 6, from the PRBS data signal. The figure shows the influence of the UTC bias conditions on the transmitted signal, with an eye opening of 723 ps in the best case, with the UTC biased at 2 mA photocurrent and 2 V.

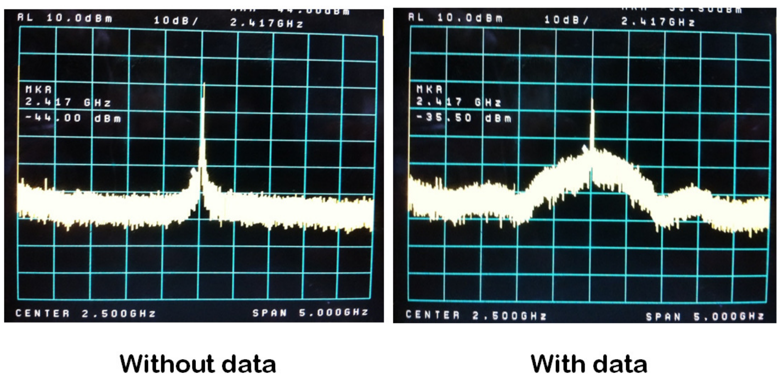

Fig. 5. Traces of the IF spectrum at 2.5 GHz.

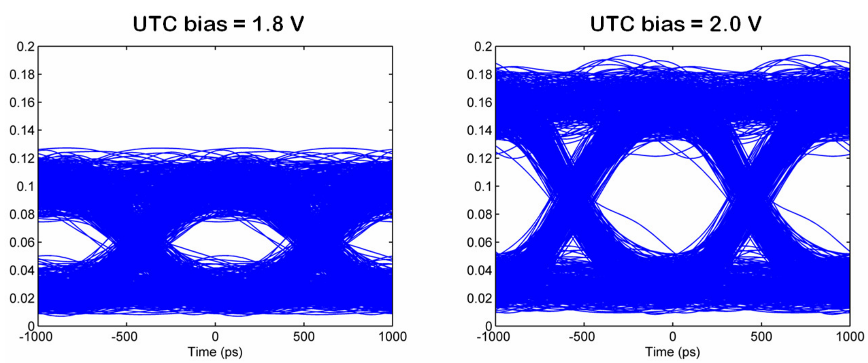

Fig. 6. Eye diagram from the envelope of the PRBS data signal under different biasing conditions of the UTC-PD.

4. Conclusion

We have demonstrated a simple and cost effective system for optical millimseter-wave generation and transmission of 1-Gb/s non-return-to-zero (NRZ) on-off keying (OOK) data based on a free-running monolithic dual DFB source as a carrier wave generator for a radio-over-fiber optical wireless transmission system. The tuning range allows us to target several frequency bands, from the W-band (75 – 110 GHz) and above the F-band (90 – 140 GHz).

We demonstrate the successful transmission on a carrier wave at 146 GHz, within the receiver 140 – 220 GHz band. This carrier frequency lies within the atmospheric windows that will permit the development of broadband wireless access technologies for future RoF-based optical–wireless networks, providing the required increase of user bandwidth.

Acknowledgments

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