Generation of multi-carrier based on a recirculating frequency shifter with delay interferometer*

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Recirculating frequency shifter (RFS) can generate stable multi-carrier, but the carrier-to-noise-ratio (CNR) is limited because noise is accumulated round by round in the recirculation loop structure. A modified RFS with a delay interferometer (DI) is proposed in this paper. The DI can suppress the accumulated noise, and enhance the CNR of multi-carrier. The principle of the generation of high quality multi-carrier based on an RFS with DI is analyzed theoretically. 50 stable carriers with spacing of 10.7 GHz are successfully generated. The flatness of 50 stable carriers is 3 dB, and the CNR is 43 dB which is increased by 3 dB compared with the structure without DI.

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100 Gbit/s Ethernet is currently available in commercial system, and Terabit/s Ethernet has already been mentioned as a future direction for transport system evolution[1]. Multi-carrier is suitable for the high capacity system, and is becoming a hot research topic[2,3]. Supercontinuum technique based on fiber nonlinear effects is a way to generate multi-carrier[4,5], but the generated carriers are sensitive to nonlinear propagation effects. Using cascaded phase modulator or adding an intensity modulator behind can generate multiple optical subcarriers[6-8]. However, due to the limited amplitude of the radio frequency (RF) signals on the phase modulator, the number of optical subcarriers is limited. Moreover, the generated multi-carrier is not flat. Recirculating frequency shifter (RFS) structure can generate a large number of carriers[9-13], but the carrier-to-noise-ratio (CNR) of the generated carriers is limited because of the noise accumulation in loop.

In this paper, we propose and experimentally demonstrate an RFS with delay interferometer (DI) to generate high quality multi-carrier. The principles of multi-carrier generation and reducing noise accumulation in loop by DI are analyzed. Finally, 50 stable high-quality carriers with spacing of 10.7 GHz are successfully generated, whose flatness is less than 3 dB and CNR is 43 dB.

As shown in Fig 1, the RFS with DI structure consists of a continuous wave (CW) laser as the seed laser for loop, a 50:50 coupler, an in-phase and quadrature (I/Q) modulator, an erbium doped fiber amplifier (EDFA) to compensate the frequency conversion loss, a band pass filter (BPF) to control the number of carriers, two polarization controllers (PCs) to assure polarization alignment, a DI to reduce the accumulated noise in loop, and an optical spectrum analyzer (OSA) to measure the result.

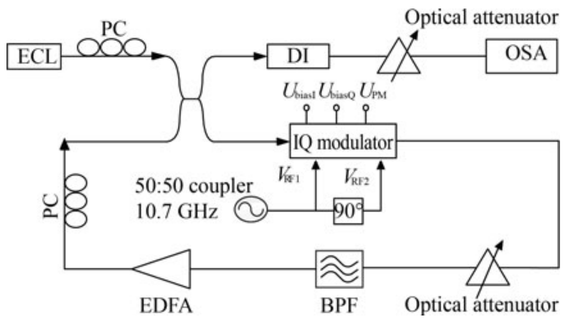

Fig.1 Schematic diagram of the RFS with DI structure used in the experiment

I/Q modulator is driven by two RF signals with frequency of f_s. The CW lightwave from laser represented as $E_{in}=E_0\exp(j2\pi f_0 t)$ is modulated by I/Q modulator, where f_0 represents the seed frequency. The output of the I/Q modulator after the first cycle can be approximately expressed as

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$$E_{out} \approx E_0 \exp(j2\pi f_0 t)[\cos(2\pi f_s t) + j\sin(2\pi f_s t)] = K\exp[j2\pi(f_0 + f_s)t] . \quad (1)$$

It means that a shifted frequency of $f_1 = f_0 + f_s$ is produced. Due to the recycle structure, a series of shifted frequencies of $f_2 = f_0 + 2f_s$, $f_3 = f_0 + 3f_s, \cdots, f_n = f_0 + nf_s$ can be produced.

Multi-carrier is produced by the RFS structure, but the noise also accumulates. A DI before the OSA can reduce the accumulated noise. DI structure is shown in Fig.2, which has two arms. In upper arm, the input signal is delayed by one symbol duration of T_s. In the other one, an adjustable phase shift (PS) of φ can be accomplished. The output of DI can be described as

$$g(t) = [f(t)\exp(j\varphi) + f(t - T_s)] / 2 , \quad (2)$$

where $f(t)$ represents the input of DI, and $T_s = 1/f_s$.

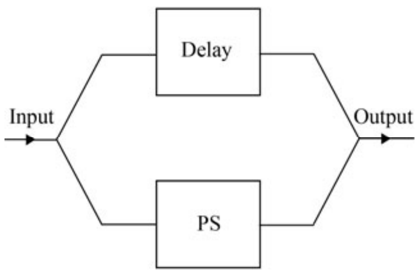

Fig.2 Schematic diagram of the delay interferometer structure

$G(\omega)$ represents the output power spectrum density (PSD) from DI, which can be expressed as

$$G(\omega) = |FFT[g(t)]|^2 = \left|\sqrt{2 + 2\cos(\varphi + \omega T_s)} \times \exp\{j\arctan[\frac{\sin(\varphi) + \sin(-\omega T_s)}{\cos(\varphi) + \cos(-\omega T_s)}]\}F(\omega)/2\right|^2 = [1 + \cos(\varphi + \omega T_s)]|F(\omega)|^2 / 2 . \quad (3)$$

The frequencies of carriers ω_n are $\omega = \omega_n = 2\pi f_0 + 2n\pi f_s$. Adjusting the phase shift φ to satisfy $\varphi + \omega_n T_s = 2k\pi$, constructive interference occurs at ω_n, and $G(\omega_n) = |F(\omega)|^2$ reaches the maximum, which equals the input. At the same time, the destructive power occurs at other frequencies where the most of noise is located. The accumulated noise reduces by this way. The output of broadband amplified spontaneous emission (ASE) noise through DI is shown in Fig.3. The results are measured by OSA with the resolution of 0.01 nm. Compared with the structure without DI, the power of ASE noise reduces by 3 dB in each Δf=10.7 GHz interval as

$$P_{out,ASE} = \int_{f_i}^{f_i + \Delta f} G_{in,ASE}[1 + \cos(\varphi + \omega T_s)] / 2 d\omega = G_{in,ASE}\Delta f / 2 + G_{in,ASE} \sin(2\pi f T_s + \varphi)\Big|_{f_i}^{f_i + \Delta f} / 2T_s = P_{in,ASE} / 2 , \quad (4)$$

where $\Delta f = 1/T_s$, f_i is the beginning of each interval, and $G_{in,ASE}$ represents the power spectrum density (PSD) of ASE noise.

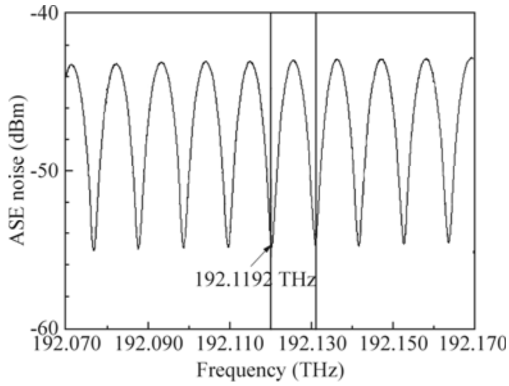

Fig.3 The output of broadband ASE noise through DI

In our experiment, the center wavelength of the laser source is 1559.5 nm. The frequency of two RF signals of 10.7 GHz is used to drive the I/Q modulator. Firstly, amplitudes, phases of RF signals and direct current (DC) bias for I/Q modulator are all adjusted to assure high quality of carrier without starting loop. The result influences the flatness of multi-carrier due to the harmonic crosstalk. The optical spectrum of the generated carrier is shown in Fig.4. The results are measured by OSA with a resolution of 0.01 nm. Compared with the maximum harmonic crosstalk, the power of the carrier is about 37 dB larger.

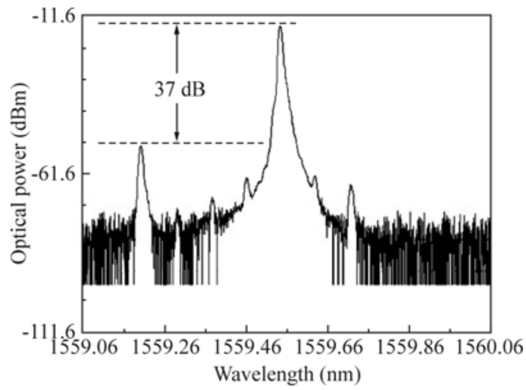

Fig.4 Optical spectrum of the generated carrier without starting loop

In the loop, the 3 dB bandwidth of BPF is about 4.4 nm to allow 50 carriers to pass. An EDFA with saturation output power of 25 dBm is used to compensate the frequency conversion loss. Adjust the polarization controller to control the polarization state which influences the flatness of multi-carrier. As shown in Fig.5, because the multi-carrier can be applied in the high speed transmission, the interesting band for each sub-carrier is from point A to point B, where A and B are the middle points of two sub-carriers, respectively. The final result of CNR for multi-carrier is the worst one of all sub-carriers. As shown in Fig.6, without DI, the generated 50 carriers only have the CNR of 40 dB. Use the DI with delay of T_s=93.46

ps (T_s=1/f_s), and adjust the phase shift to reach a proper φ before OSA. Finally, we generate 50 high-quality carriers shown in Fig.7. These stable carriers with spacing of 10.7 GHz have the flatness less than 3 dB and CNR of 43 dB. The CNR is increased by 3 dB compared with the structure without DI as calculated in Eq.(4). These results are measured by OSA with the high-resolution of 20 MHz.

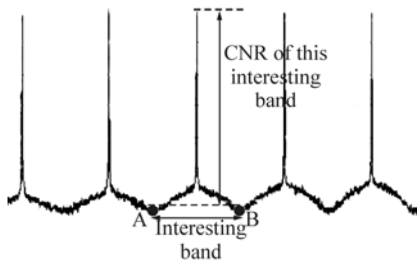

Fig.5 Definition of interesting band and CNR

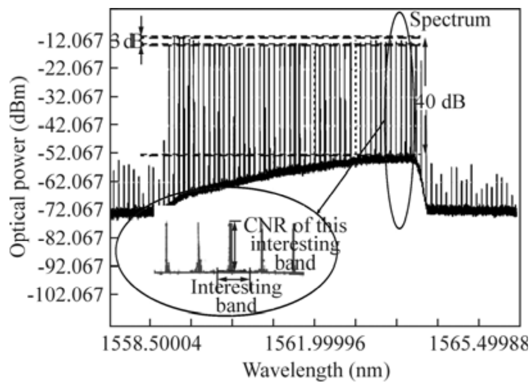

Fig.6 The 50 generated carriers without DI

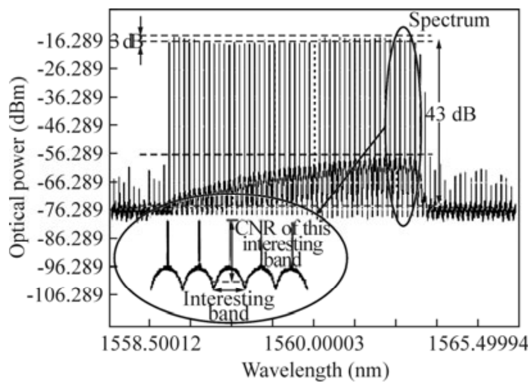

Fig.7 The 50 generated carriers with DI

In this paper, we propose an RFS with DI to generate high-quality multi-carrier. The operating principle of generating multi-carrier and reducing noise accumulation in loop by DI is analyzed. The CNR is improved significantly because of the decrease of the accumulated noise in loop by DI. Finally, stable carriers with spacing of 10.7 GHz are realized in the experiment, whose flatness is 3 dB and CNR is 43 dB. The CNR is increased by 3 dB compared with the structure without DI.

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