Generation of frequency harmonics for QKD systems at subcarrier waves

N D Gerasimenko¹, V S Gerasimenko¹
Scientific supervisor V M Petrov¹
¹ ITMO University, Saint-Petersburg, Russia
e-mail: nat-komolova@yandex.ru

Abstract. This paper demonstrates the efficiency of using optical feedback without amplifiers to generate subcarrier waves in the microwave phase modulator output spectrum for quantum communications. It is proposed ideas for expanding the functionality of quantum communication systems and communication systems using DWDM standarts

1. Introducing.
For quantum communication systems (for example based on the principle of quantum key distribution at subcarrier waves) phase and amplitude modulators are needed. The amplitude modulator provides the input of the transmitted information, and the phase modulator is required for its transmission. Usually for transmission a pair of subcarrier frequencies $F \pm f$ is used (it occurs during phase modulation at the carrier frequency $F$). [1]

For practical use an important factor is the key transmission rate. It can be enlarged by increasing the number of used side frequencies. The easiest way to do this is to create a feedback for multiple modulation.

2. History.
There are a lot of experiments using feedback in combination with a microwave modulator. Typical scheme is shown at figure 1. It consists of X-beam splitter, in which one input and output are used to create a feedback loop, the second input is required to input radiation, and the second output is required to output radiation to a photodiode or spectrum analyzer. It is also proposed to use an amplifier to compensate for losses, and it makes scheme inapplicable for quantum communication systems due to the impossibility of photon cloning. Either, the use of an amplifier leads to an increase in noise at the main frequencies of the resonator. [2]

![Figure 1. The frequency comb generator circuit](image)

Another type of experiment involved placing a modulator between Bragg mirrors (figure 2). However, due to the peculiarities of the reflection band of the mirrors, a spectral dip with a width of...
several teeth appears in the output comb (figure 3), and the use of an amplifier is required for compensating it. [3]

Figure 2. Experimental setup. Figure 3. Output spectrum.

So the development of a scheme for generating optical frequency combs without using an amplifier is extremely important for quantum communication systems.

3. Experiment.
We designed [4] the following scheme (figure 4): the radiation from the laser passed through a phase modulator of our own production, then through a divider. Light from one output of divider entered the spectrum analyzer, and the second output was connected to the input of the modulator and formed an optical feedback loop in the form of a fiber segment. A standard optical connector was placed approximately in the middle of the loop, allowing the feedback to be “turned on” and “turned off”.

Figure 4. Installation block diagram. 1 - laser, 2 - FM modulator, 3 - optical spectrum analyzer, 4 - microwave generator, 5 - Y-formed directional coupler, 6 - optical connector.

In the experiment, we used 1:3 and 1:9 beamsplitters. The greatest influence of feedback was found for a 1:9 beam splitter, so further experiments were carried out with it. The results are shown at figure 5. The maximum number of subcarrier was 40 pieces (20 in each direction from the carrier).
4. Analysis

We have investigated the influence of phase modulation frequency (figure 5 left) and the influence of the input power of the phase modulation signal on the number of subcarrier waves (fig. 5 right) (length of the feedback loop was fixed).

In figure 6 shows the dependence of the number of spectral components with the feedback on the modulation frequency at a power of 25 dBm - with a step of 5 MHz. Red dots are the experimental data and blue lines are their interpolation. The graph shows that the maximum number of spectral components was observed at a modulation frequency of 1.725 GHz and amounted to 40 pieces.

In figure 7 shows the effect of the input power of the phase modulation signal on the number of side frequencies. As our additional analysis showed, this dependence is close to quadratic.

A clearly pronounced symmetry of the dependence (fig. 6) was observed to decrease and increase the modulation frequency in the vicinity of the peak. An increase in the number of maxima at the edges of the investigated region is associated with the following peaks, i.e., a periodicity of the dependence is observed. This is easily explained by the laws of resonance: for resonance to occur, it is necessary that an integer number of microwave wavelengths fit into the length of the feedback loop \( l = c/F = 0.1738 \text{ m} \). In our work, the length of the feedback loop was \( L = 8.53 \text{ m} \), and then 49 microwave wavelengths fit into it.
By varying the feedback length it is possible to select F so that it matches to the standard DWDM frequency grid (with a step of 25, 50 or 100 GHz). Then one laser can be used to work in several frequency channels simultaneously. Also interesting variant is to "fit" a lot of spectral channels at once in the band of one standard spectral channel.

It should also be noted that for the occurrence of correlations between subsequent pulses, it is necessary that the pulses overlap each other when propagating through the modulator. Since the typical pulse repetition rates in QKD systems are limited to values of about 100 kHz-1 MHz, and the length of the feedback loop does not exceed 10 m, successively passing pulses will have time to decay by values of the order of 60 dB. However, when a modulator with a fiber resonator is introduced into real QKD systems, it is possible to replace the static beam splitter with an electro-optical splitter in order to completely get rid of the traces of the previous pulse before introducing a new pulse into the system.

Directions for further research are also outlined. Obviously, if the introduced phase changes with several successive passes of one pulse through the modulator, then the phase incursions should add up. However, this may slightly change the shape of the comb. This is because the insertion phase is determined by the applied voltage of the modulating signal. In the future, we plan to investigate the features of the passage of a pulse through the resonator depending on the optical resonance.

Another important area of research is the use of one of the subcarrier waves as a new optical carrier.

5. Conclusion

So in this work we have demonstrated the effectiveness of using optical feedback for increasing the number of subcarrier waves. Our scheme does not use amplifiers, which allows it to be used for quantum communication systems, in addition, it is extremely simple engineering. A large number of subcarrier waves can be as additional data protection when information transmitted on different pairs of subcarriers. It also reduces the requirements (and cost) of the equipment used, such as a microwave generator, since operating on a larger subcarrier number allows a decrease in the phase modulation frequency. Either we proposed some ideas to expand the capabilities of quantum communication systems.

References

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