INVESTIGATION OF INFLUENCE OF TIME-BANDWIDTH PRODUCT OF CHIRPS ON EFFECTIVENESS OF THEIR PROCESSING BY TUNEABLE ACOUSTO-OPTIC MATCHED FILTER

Yuri G. Antonov, Victor N. Ushakov

Department of theoretical fundamentals of radioengineering, Saint-Petersburg Electrotechnical University, 5 Prof. Popov st., Saint-Petersburg, 197376 Russia.
E-mail tor@eltech.ru, phone +7(812)234-1584.

ABSTRACT

Tuneable acousto-optic matched filters (AOMF) have good prospects on raising effectiveness of noiseproof wide band radio communication systems.
In this paper a tuneable AOMF is investigated, with liquid-crystal phase mask (LCPM) being important element of this filter. Insufficient resolution of AOMF can result in decreasing of output signal peak. The attempt to increase density of LCPH elements results in technical difficulty of its manufacturing and rising its cost and the advantage can be insignificant. In this paper the dependence of minimum quantity LCPH elements vs. chirp time-bandwidth product is investigated to make the number of elements of LCPH as little as possible with the losses don't exceeding a given value.

KEYWORDS

Acousto-optic matched filter, chirp, liquid-crystal phase mask, impulse response, models, algorithm.

1. INTRODUCTION

The use of wide band pulses and appropriate matched filters in receiving devices allows to solve successfully important radio engineering problem of noiseproof radio communication.
In some cases acousto-optic matched filters can be expediently used as matched filters. Advantages of such filters are simplicity of matched processing realisation for wide band pulses in real time, rather small dimensions and power consumption – ref. 1. If a chirp with small duration (several microseconds) is required to use in radio technical system, the Gerig-Montague's filter can be applied for matched processing of such signal – ref. 2.
Currently the simplicity of wide band (100 MHz and more) chirps generation and their good correlation properties attract developers of specialised noiseproof communication systems transmitting sequences of chirps with pulse modulation. But at designing such systems of radio communication the following problem arises. The law of instantaneous frequency changes can not be formed strictly linear with the help of varicap. Besides, when the environment temperature varies, the parameters of generator driving elements vary too, and thus the frequency modulation law of pulse also varies. It is necessary to note that the generated pulses have good repeatability from pulse to pulse during a few tens of minutes. If the filtering is made by AOMF with fixed impulse response (IR), the parameters fluctuation of the pulse frequency modulation law results in significant losses.
Modified Gerig-Montague's AOMF with added electronic controllable liquid-crystal phase mask is described in ref. 3. That filter has allowed to control IR of AOMF in some limits and optimally process quasi-chirps with frequency modulation law different from linear. The reconstruction of the IR in this modified AOMF is performed by correction of light phase front with the help of LCPH. The mathematical model of such filter and some results of modelling is presented in refs. 4, 5. At the same place the adaptation algorithm for this tuneable AOMF that allows automatically to adjust IR of AOMF according to receiving chirp parameters and thus allows to avoid energetic losses caused by mismatching of filer and chirp is described.
However, the results presented in refs. 4, 5 have been obtained in assumption that LCPH phase function, adjusting light phase front, is continuous, but actually it is not so. Phase function of LCPH is discrete-value, as LCPH consists of discrete phase turning elements. This circumstance leads to additional energetic losses.
This paper considers practically important question about minimising the number of elements in LCPH so that, on the one hand, energetic losses would not be significant and, on the other hand, LCPH control scheme can be made simple and cheap.
It should be noted, that, according to results presented in refs. 4, 5, maximum energetic losses are observed when the parameter describing velocity of increasing the chirp frequency is changed, so in this paper the situation of matching the chirp and tuneable AOMF is considered vs. this parameter.

2. FUNCTIONAL DIAGRAM OF TUNABLE AOMF

A functional diagram of the tuneable AOMF for processing of chirps is shown in fig. 1. A principle of its functioning is as follows. The chirps act on the input of the power amplifier (PA). Then they act on the input of AOMF with LCPM. Light from a laser source (LS) passes through a lenses L1 and L2, then through acousto-optic modulator (AOM) and LCPM. Then the light is gathered in the area of the photodetector (PD). A main element of PD is the avalanche photodiode (APD). The registered signals from PD are useful and are the output signals. These signals act on the peak detector (PkD) which fixes their level, and then act on the microcontroller (MC). To constrain the level of output pulses in given limits MC carries out control of 1) LCPM on specially developed algorithm - refs. 4 and 5, 2) reverse-bias voltage of APD, 3) AGC and 4) AFC.

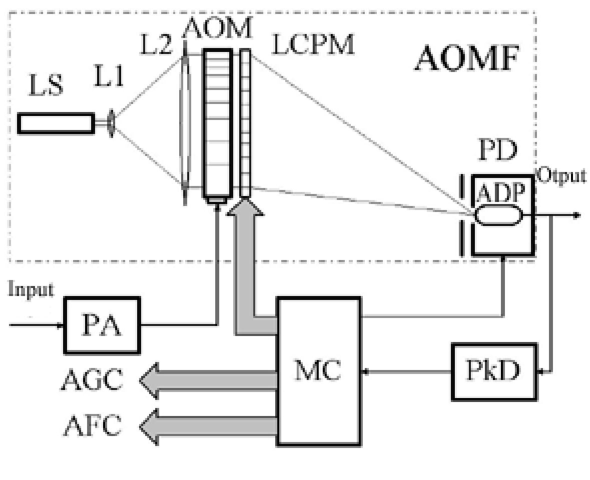

Fig.1.

3. ENERGETIC LOSSES CAUSED BY DISCRETE-VALUE NATURE OF CORRECTING PHASE FUNCTION

We consider a prototype chirp, for that the tuneable AOMF is built. Variation of instantaneous frequency is described by the following law:

$f(t) = f_0 + \gamma_n \cdot t,\ t \in [0; \tau_n]$ (1)

Here f_0 is the lowest frequency value in the chirp; γ_n is the parameter describing the velocity of instantaneous frequency variation in the chirp; τ_n is the duration of chirp. Subscript n is used for describing the values related to the prototype chirp. Parameter γ_n can be expressed through efficient spectrum width and duration of prototype chirp:

$$\gamma_n = \frac{\Delta f_n}{\tau_n}, \qquad (2)$$

where Δf_n is efficient bandwidth of prototype chirp.

The parameters of actually received chirps differ from parameters of the prototype chirp. Relative mistuning measure of parameter γ_n is defined as

$$\delta\gamma_n = \frac{\Delta\gamma_n}{\gamma_n}, \qquad (3)$$

where $\Delta\gamma_n = \gamma_n - \gamma$. In this expression γ describes velocity of frequency change in the actually received chirp.

To perform matched receiving of chirps which parameters differ from prototype chirp parameters it is necessary to reconstruct the IR of AOMF in appropriate way ref. 5. Two situations are possible: the reconstruction of IR is performed with the help of LCPH only; the reconstruction of IR is performed with the help of LCPH and appropriate changing (tuning) of chirp middle frequency. The tuning of chirp middle frequency allows to build correcting phase function of LCPH more suitable for realisation. Examples of correcting phase function for both cases are given below. Since real LCPH consists of a limited number of phase turning elements, the phase function of LCPH is discrete-value. This circumstance is reflected on the figures by piece-constant lines (fig.2 and fig.3).

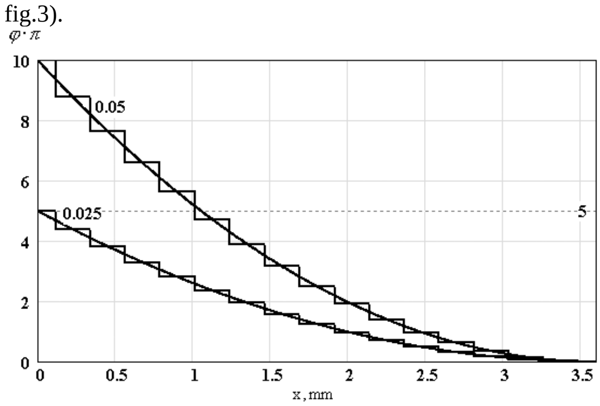

Fig. 2.
Correcting phase functions without tuning of chirp middle frequency for $\delta\gamma = 0.05$ and 0.025.

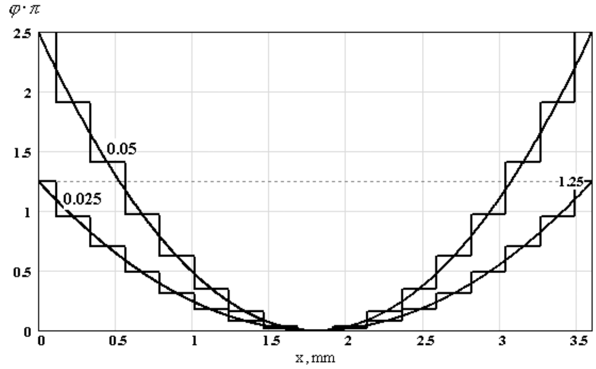

Fig. 3.
Correcting phase functions with tuning of chirp middle frequency for $\delta\gamma = 0.05$ and 0.025.

At the given figures smooth lines are desired and piece-constant lines are real.

Shown curves have been built for different values of mistuning of parameter describing velocity of chirp frequency change. By comparing two figures we can see that in the case when tuning of chirp middle frequency is implemented, the same mistuning of parameter γ leads to four times less maximum phase shift. It essentially reduces the requirements to the LCPH in both the degree of its discreteness (as will be shown below) and materials from which LCPH is fabricated. Discrete-value nature of correcting phase function results in mismatching of filter IR and correspondent chirp. This circumstance is the reason of the arising losses that will be considered below. To estimate such losses the simulation of tuneable AOMF working in conformity with determinate model described in refs. 4, 5 has been performed. As a result of simulation the curves of energetic losses vs. the number of elements in the LCPH for different mistuning degree of parameter $\delta\gamma_n$ have been calculated. The calculations have been performed for two cases: with and without the tuning of chirp middle frequency. Figures 4 and 5 give these curves, the following parameters of prototype chirp have been assumed: $\tau_n = 1 \quad \mu s$, $\Delta f = 100 \quad MHz$.

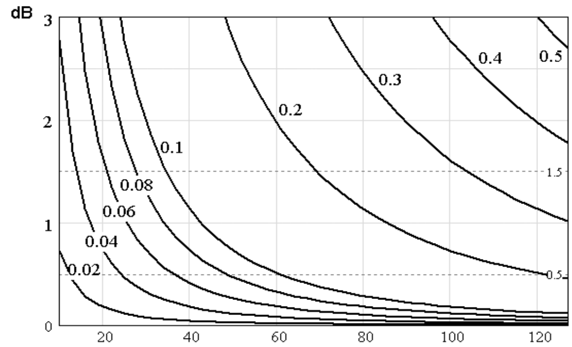

Fig. 4.
Energetic losses vs. the number of elements in the LCPH for different mistuning $\delta\gamma_n$ when tuning of chirp middle frequency is not performed.

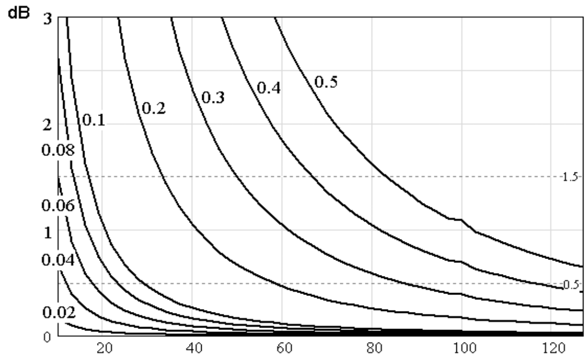

Fig. 5.
Energetic losses vs. the number of elements in the LCPH for different mistuning $\delta\gamma_n$ when tuning of chirp middle frequency is performed.

The curves on the figures shows that the energetic losses are reduced when the number of samples in the LCPH is increased, and the more severe mistuning is to be corrected, the more the curve is shifted to the upper right corner of the graph. To hold, therefore, the losses at the same level when the mistuning increases, it is necessary to use the LCPH with increased number of samples. When the prototype chirps act on the input of tuneable AOMF, the correction of phase function is not required and for this reason the curve correspondent to the non-mistuned chirp (prototype chirp) does not depend on the number of samples in the LCPH.

The comparison of two figures shows that in the second case, when the tuning of chirp middle frequency is performed, the requirements for the number of samples in the LCPH are dramatically reduced (the same loss in both cases is assumed). The correcting phase function, therefore, should be optimised so that its maximum values were so less as possible. This optimisation, for example, can be done through tuning of middle frequency, as was shown above.

Thus the figures, important for actual practice, have been obtained by modelling. Using this figures, we can easily determine the minimum number of elements in the LCPH that gives not significant loss when the chirps with fluctuating in given range (given mistuning $\delta\gamma_n$) parameter γ are processed. The curves have been obtained with assumption that tuneable AOMF is built for a certain prototype chirp with parameters γ_n and Δf_n, but it appears that the significance has only the time-bandwidth product of chirp:

$$B = \Delta f \cdot \tau \text{ and } B_n = \Delta f_n \cdot \tau_n = 100 . \quad (4)$$

The obtained curves are correct for any chirps with time-bandwidth product is equal to 100. Furthermore, we can use these results, not fulfilling simulation, for chirps with time-bandwidth product differing from that of prototype chirp if the normalisation of mistuning function $\delta\gamma_n$ is produced in the following way:

$$\delta\gamma = \delta\gamma_n \cdot \frac{B_n}{B} . \quad (5)$$

For example, when tuneable AOMF for chirps with time-bandwidth product equal to 200 is required to be built, we can use the figures given above to find out the minimum number of LCPH elements but we have to divide the available mistuning $\delta\gamma_n$ by two. So, the curve corresponding to the mistuning $\delta\gamma_n = 0.2$ shall now correspond to the mistuning $\delta\gamma = 0.1$.

We prove this circumstance. First we assume that duration of prototype chirps and duration of chirps with time-bandwidth product B are equal, then from the formula (3) it follows that for filter constructed for prototype chirp

$$\delta\gamma_n = \frac{\Delta\gamma_n}{\gamma_n}, - \quad (6)$$

and for filter constructed for chirp with time bandwidth product B

$$\delta\gamma_B = \frac{\Delta\gamma_B}{\gamma_B}. \quad (7)$$

We can write the following identity:

$$\frac{B}{B_n} \cdot B_n = B . \quad (8)$$

It is transposed to

$$\frac{B}{B_n} \cdot \Delta f_n \cdot \tau_n = \Delta f_B \cdot \tau_B . \quad (9)$$

And the following transformation with account that the durations of chirps are equal ($\tau_n = \tau_B$) gives:

$$\frac{B}{B_n} \cdot \gamma_n = \gamma_B . \quad (10)$$

There is now the common expression to be written that describes phase function vs. time that should be compensated to match the filter and the chirp:

$$\varphi(t) = 2 \cdot \pi \cdot \int_0^t \Delta\gamma \cdot t \quad dt = \frac{\Delta\gamma \cdot t^2}{2} . \quad (11)$$

In the case when the filter for prototype chirp is considered in expression (11) we should assume $\Delta\gamma = \Delta\gamma_n$ and in another case, when the filter for chirp with time-bandwidth product B is considered, $\Delta\gamma = \Delta\gamma_B$. It is important to note that when the same phase function $\varphi(t)$ is compensated, the requirements to the LCPH will be the same and the required number of elements will be the same too. So that this phase function should be the same in both cases (when the filter is built up for prototype chirp and when the filter is built up for the chirp with time-bandwidth product B) it is necessary that absolute mistunings of parameter γ should be equal:

$$\Delta\gamma_n = \Delta\gamma_B \quad (12)$$

Using formulas (6), (7) and (12), we obtain

$$\delta\gamma_n \cdot \gamma_n = \delta\gamma_B \cdot \gamma_B . \quad (13)$$

And finally, using the expression (10), we can write

$$\delta\gamma_B = \delta\gamma_n \cdot \frac{B_n}{B} . \quad (14)$$

The expression (14) is conformed with expression (5), so the first half of proof is completed.

The obtained expression can be treated in the following way: the corresponding mistuning is reduced by B/B_n times if the chirp bandwidth is increased by B/B_n times but the duration of chirp is maintained constant.

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Let's assume now that the bandwidth of chirp Δf is maintained constant. Then we can find out from the identity (9) that the duration of chirp with time-bandwidth product B is connected with duration of prototype chirp in the following way:

$$\tau_B = \tau_n \cdot \frac{B}{B_n}. \tag{15}$$

Using the formulas (2) and (15) and the circumstance that the bandwidth of chirp is constant, we can obtain the following equation:

$$\gamma_B = \gamma_n \cdot \frac{B_n}{B}. \tag{16}$$

Now we can determine the phase functions vs. time:

$$\varphi_n(t) = \frac{\Delta\gamma_n \cdot t^2}{2}, \ t \in [0 \quad ; \quad \tau_n]; \tag{17}$$

$$\varphi_B(t) = \frac{\Delta\gamma_B \cdot t^2}{2}, \ t \in [0 \quad ; \quad \tau_B]. \tag{18}$$

Changing of chirp duration by the factor B/B_n leads to the dimensions of LCPH correspondingly changed by B/B_n times. This circumstance does not have any essential role, because with the help of optical scheme the light window aperture can be easily scaled.
Essential is just the number of elements in the LCPH. Therefore, without loss of generality the corresponding scaling of the phase function (18) can be carried out:

$$\varphi_B(t) = \frac{\Delta\gamma_B \cdot t^2}{2} \cdot \left(\frac{B}{B_n}\right)^2, \ t \in [0 \quad ; \quad \tau_n]. \tag{19}$$

Using the LCPH with the same parameters in the matched filter for chirp with time-bandwidth product B and in the matched filter for prototype chirp calls for the equality of phase functions (17) and (19), thus we can find out

$$\Delta\gamma_n = \Delta\gamma_B \cdot \left(\frac{B}{B_n}\right)^2. \tag{20}$$

Finally, using equations (6), (7), (16) and (20), we can easy derive:

$$\delta\gamma_B = \delta\gamma_n \cdot \frac{B_n}{B}. \tag{21}$$

The expression (21), as also (14), is conformed with expression (5), so the second half of proof is completed.
The obtained expression can be treated in the following way: the corresponding mistuning is reduced by B/B_n times if the chirp duration is increased by B/B_n times but duration of chirp is maintained constant.
In general, noting that changing either bandwidth or duration of chirp by some factor leads to changing the time-bandwidth product of chirp by the same factor, we make generalisation: to estimate the minimum number of elements in the LCPH for processing the chirp with time-bandwidth product B by the tuneable AOMF we can use the curves given at the figures 4 and 5, that have been obtained for matched filter processing the prototype chirp with time-bandwidth product $B_n = 100$, but at this case the mistunings $\Delta\gamma_n$, indicated at the figures, should be divided by B/B_n.

4. CONCLUSION

The practically important figures of energetic losses taken place in tuneable AOMF for prototype chirp with time-bandwidth product equal to 100 vs. the number of phase tuning elements in the LCPH are obtained. As was expected, on the one hand, the higher is the number of elements in the LCPM, the less losses are observed in the tuneable AOMF. On the other hand, the more is the mistuning range of IR of tuneable AOMF, the higher is the required number of elements in the LCPH.
The proof of circumstance that the figures of energetic losses obtained as a simulation result and taken place in the tuneable AOMF for prototype chirps with time-bandwidth product equal to 100 have general character have been fulfilled, and after proper normalisation the obtained results can be easily used to estimate the number of elements in the LCPH when the tuneable AOMF for chirps with time-bandwidth product different from 100 is required to build.

REFERENCES

1.Ушаков В.Н., Егоров Ю.В. и др. Функциональные устройства обработки сигналов. М.: Радио и связь 1987.
2.J.S.Gerig, H.Montague. A Simple Optical Filter for Chirp Radar //IEEE Proc.- 1964.- V.52(12), p.1753.
3. Grachev S.V., Rogov A.N., Ushakov V.N., "Acousto-optic matched filters with electronic adjusting, based on liquid crystal mask", Proc. of 2nd European Acousto-Optic Club Meeting "Advances in acousto-optics (AA-O'97)", June 24-25, 1997., St.Petersburg, p.80-83.
4. Yuri G. Antonov, Andrew N. Rogov, Victor N. Ushakov, «Adaptation Algorithm For Chirp Acousto-Optic Matched Filter», Proc. SPIE, vol. 3900, pp.236-241.
5. Ю. Г. Антонов, А. Н. Рогов, В. Н. Ушаков. Алгоритм адаптации перестраиваемого акустооптического согласованного фильтра для ЛЧМ-импульсов. IEEE / ICC2001 / St. Petersburg. International Conference on communications. 11-15 июня 2001 г.