INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 2, PP. 437-442
Manuscript received January 22, 2024; revised June, 2024. doi: 10.24425/ijet.2024.149563

The ambiguity of frequency determination in digital microwave frequency discriminators

Hubert Stadnik, and Bronisław Stec

***Abstract*—Instantaneous frequency measurement devices are designated for very fast measurements of the current frequency value of microwave signals, even if they are very short in the time domain. Fast measurements of frequency temporary values may be based on the evaluation of the phase difference of signal propagating through the microwave transmission lines with unequal, but known, lengths. This paper presents the principle of determination of temporary values of the microwave signal frequency using the digitalized signals and the binary value of them eventually. In the purpose of increase the frequency discrimination resolution, additional tracks with lines with a larger length are proposed. For the system with elements with analytical model transmission characteristics it is typical that bands of ambiguity of frequency measurement occurs. To tackle this problem in addition to 4 x 4 Butler matrix implementation the method of using combination sine and cosine signals is proposed.**

***Keywords*—microwave frequency discriminator; microwave phase discriminator; instantaneous frequency measurement; ambiguity of frequency determination**

I. Introduction

MICROWAVE frequency discriminators (MFD) are devices used to develop information on the temporary values of frequency of the received signal [1-4]. This task can be completed by systems with frequency conversion, systems with microwave resonators or even band-stop filters. Very good results of immediate broadband measurement of the frequency of microwave signals are achieved by devices where the interferometric properties are used [1-3]. The results, slow-changing amplitude signals are obtained almost in no time. Their value depends on the frequency of the input signal. The measurement delay results only due to signal propagation time through a few microwave elements. Thanks to that benefits, it is widely used as the main part of instantaneous frequency measurement (IFM) receivers [5]. The overall structure of the discriminator consists of the element that develop two signals, whose phase difference is proportional to the frequency of the input signal. Most popular of the possible implementations of this task consists of a signal splitting element and two transmission lines of different lengths [6]. Next element of MFD is the microwave phase detector system (MPhD), which is designed to generate slow-changing signals proportional to the phase difference of the two signals obtained at an earlier stage. To increase the frequency discrimination resolution, lines with a larger length can be used. However, it should be noticed that such a procedure narrows the measurement unambiguity band [4, 7]. For correct operation, several frequency discriminators with different line length may be used parallel. With the increase in the number of MFD with appropriately selected line lengths, the sub bands for unambiguous frequency detection may be determined.

To facilitate process of frequency measurement it is possible to convert sine and cosine signal to it digital value and based on it define the frequency value. Such type of device is called digital IFM (DIFM). In the way of multiplying measurement tracks of DIFM it is feasible to achieve frequency detection in wide frequency band. Everything works well for idealistic transmission characteristic based elements. However for real device the bands of ambiguity of frequency measurement occurs.

In this paper is going to be presented such device based on interferometer using 4x4 Butler matrix as well as the method of how to tackle the ambiguity of frequency measurement that appears when the elements with real characteristics (which can be substituted with its analytical models) are implemented.

II. Operation of Microwave Frequency Discriminator

THE interferometric MFD consists of two basic functional blocks. First is the system generating two signals u_{w_1} and u_{w_2} which phase difference is proportional to the frequency f of the input signal (1), after that there is the microwave phase detector.

$$u_{we} = U_{we} \cdot e^{j(2\pi f t+\varphi_w)} \tag{1}$$

The first stage of these systems consists of the power splitter PS or in some applications may be directional coupler (DC), which provides equal distribution of the input signal (1) energy and the delay line (SL) – figure 1.

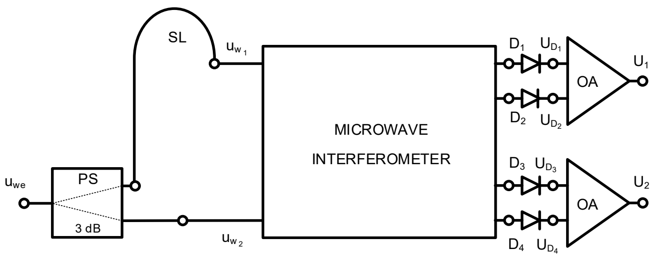

Fig. 1. Block diagram of an interferometric microwave frequency discriminator.

First Author is with Polish Air Force University, Faculty of Aviation, Dęblin, Poland (e-mail: h.stadnik@law.mil.pl).

Second Author is with Military University of Technology, Faculty of Electronics, Institute of Radioelectronics, Warsaw, Poland (e-mail: bronislaw.stec@wat.edu.pl).

After that, these signals are fed to the microwave phase discriminator system, which can be made in the form of a microwave interferometer. This system implements the appropriate division (in the matter of power level and proper phase shift relation) of the u_{w_1} and u_{w_2} signals, which in the next stage are summed vectorly. Afterwards, develops four signals $\mathrm{U}_{\mathrm{D}_1} \cdots \mathrm{U}_{\mathrm{D}_4}$ whose amplitude is slowly varying. This amplitude is obtained in the process of quadrature detection (power detection) and it value depends on the frequency of the input signal (1). That means we can estimate input signal frequency f_m.

$$f_m = f(\mathrm{U}_{\mathrm{D}_1}, \mathrm{U}_{\mathrm{D}_2}, \mathrm{U}_{\mathrm{D}_1}, \mathrm{U}_{\mathrm{D}_1}) \tag{7}$$

III. Operation of Frequency Discriminator Based on Classic Type Microwave Interferometer

The most common is the microwave interferometer of frequency discriminator build of classic layout which consist of three quadrature couplers and one power splitter – figure 2.

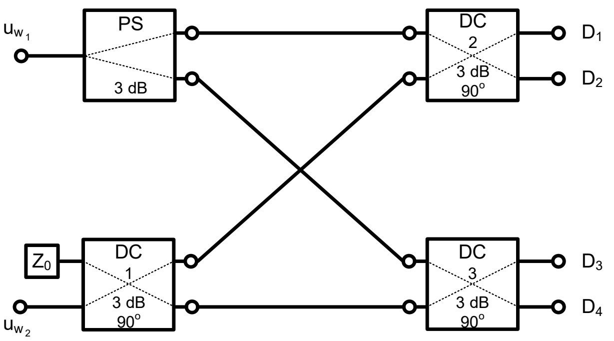

Fig. 2 Block diagram of interferometer of classic structure.

For analysis purposes the characteristic of elements may be describe as an analytical models as below (Fig. 3):

- directional coupler:
  - transmittance to direct port:

$$S_{\mathrm{CD}} = \frac{\sqrt{1-k^2}}{\sqrt{1-k^2}\, cos(\theta(f)) + j\, sin(\theta(f))} \tag{2}$$

  - transmittance to coupled port:

$$S_{CC} = \frac{jk \sin(\theta(f))}{\sqrt{1-k^2}\cos(\theta(f)) + j\sin(\theta(f))} \tag{3}$$

where: $\theta(f)$ – electrical length of the coupling area; k – coupling factor.

- Wilkinson power divider transmittance:

$$S_{\mathrm{D}} = \frac{2}{3\cos(\theta(f)) + j\, 2\sqrt{2}\sin(\theta(f))} \tag{4}$$

where: $\theta(f)$ – electrical length of the divider arm.

- delay line transmittance, which is responsible for the phase delay of the signal:

$$S_{SL} = e^{-j\gamma} \tag{5}$$

where: $\gamma = \frac{2\cdot\pi}{v}\cdot f \cdot l_{SL}$

v – propagation velocity,

l_{SL} – length of SL line.

In general considerations it is accepted that:

$$\theta = \frac{\pi}{2}\frac{f}{f_0} \tag{6}$$

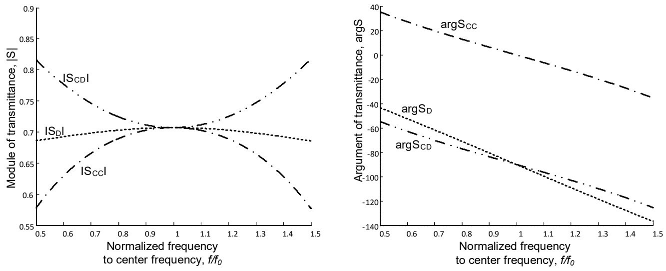

Fig. 3 Charts of an analytical models characteristics of used elements

For input signals:

$$u_{w_1} = U_{w_1} \cdot sin(\omega \cdot t + \varphi_{w_1}) \tag{7}$$

and accordingly:

$$u_{w_2} = U_{w_2} \cdot sin(\omega \cdot t + \varphi_{w_2}) \tag{8}$$

where: φ_{w_1}, φ_{w_2} – phase of signals u_{w_1} and u_{w_2} `accordingly,

We can described output signals as follow:

$$u_{D_1} = T_{1w_1} \cdot u_{w_1} + T_{1w_2} \cdot u_{w_2} \tag{9}$$

$$u_{D_2} = T_{2w_1} \cdot u_{w_1} + T_{2w_2} \cdot u_{w_2} \tag{10}$$

$$u_{D_3} = T_{3w_1} \cdot u_{w_1} + T_{3w_2} \cdot u_{w_2} \tag{11}$$

$$u_{D_4} = T_{4w_1} \cdot u_{w_1} + T_{4w_2} \cdot u_{w_2} \tag{12}$$

where: T_{iw_1} and T_{iw_2} stands for coefficients describing the signal paths from the input "1" or "2" to the output $i = 1, 2, 3, 4$. This coefficients are equal to the products of the transfer functions of individual elements on the signal way.

$$T_{1w_1} = S_D \cdot S_{CD_2} \tag{13}$$

$$T_{2w_1} = S_D \cdot S_{CC_2} \tag{14}$$

$$T_{3w_1} = S_D \cdot S_{CD_3} \tag{15}$$

$$T_{4w_1} = S_D \cdot S_{CC_3} \tag{16}$$

and

$$T_{1w_2} = S_{CC_1} \cdot S_{CC_2} \tag{17}$$

$$T_{2w_2} = S_{CC_1} \cdot S_{CD_2} \tag{18}$$

$$T_{3w_2} = S_{CD_1} \cdot S_{CC_3} \tag{19}$$

$$T_{4w_2} = S_{CD_1} \cdot S_{CD_3} \tag{20}$$

where: S_{CD} and S_{CC} stands for direct and coupled transmittance of coupler, respectively.

The interferometer output signals will be described as follow:

$$u_{D_1} = \frac{1}{2} \cdot e^{j\cdot(-\pi)} \cdot U_{w_1} \cdot e^{j(\omega t + \varphi_{w_1})} + \frac{1}{2} \cdot U_{w_2} \cdot e^{j(\omega t + \varphi_{w_2})} \tag{21}$$

$$u_{D_2} = \frac{1}{2} \cdot e^{j\cdot(-\frac{\pi}{2})} \cdot U_{w_1} \cdot e^{j(\omega t + \varphi_{w_1})} + \frac{1}{2} \cdot e^{j\cdot(-\frac{\pi}{2})} \cdot U_{w_2} \cdot e^{j(\omega t + \varphi_{w_2})} \tag{22}$$

$$u_{D_3} = \frac{1}{2} \cdot e^{j\cdot(-\pi)} \cdot U_{w_1} \cdot e^{j(\omega t + \varphi_{w_1})} + \frac{1}{2} \cdot e^{j\cdot(-\frac{\pi}{2})} \cdot U_{w_2} \cdot e^{j(\omega t + \varphi_{w_2})} \tag{23}$$

$$u_{D_4} = \frac{1}{2} \cdot e^{j\cdot(-\frac{\pi}{2})} \cdot U_{w_1} \cdot e^{j(\omega t + \varphi_{w_1})} + \frac{1}{2} \cdot e^{j\cdot(-\pi)} \cdot U_{w_2} \cdot e^{j(\omega t + \varphi_{w_2})} \quad (24)$$

For such system when it is fed with two signals u_{w_1} and u_{w_2} which phase difference is changing in the range of 0 to 360° according to frequency f of input signal u_{we}, interferometer output signals are subjected to amplitude detection. After the square detection and filtering out the high-frequency component, voltages are obtained:

$$U_{D_1} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 - k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2} - \pi) \quad (25)$$

$$U_{D_2} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 + k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2}) \quad (26)$$

$$U_{D_3} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 - k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2} - \frac{\pi}{2}) \quad (27)$$

$$U_{D_4} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 + k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2} + \frac{\pi}{2}) \quad (28)$$

where: k_d stands for proportionality factor (detection constant).

Then operation of summation properly selected pairs of detectors amplitudes by operational amplifiers gives two amplitudes which in their shapes are similar to sinus and cosines functions.

$$U_1 = U_{D_1} - U_{D_2} = k_d \cdot U_{w_1} \cdot U_{w_2} \cdot \sin(\varphi_{w_1} - \varphi_{w_2}) \quad (29)$$

$$U_2 = U_{D_3} - U_{D_4} = k_d \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2}) \quad (30)$$

The system implementing described above operations is shown in the figure 4.

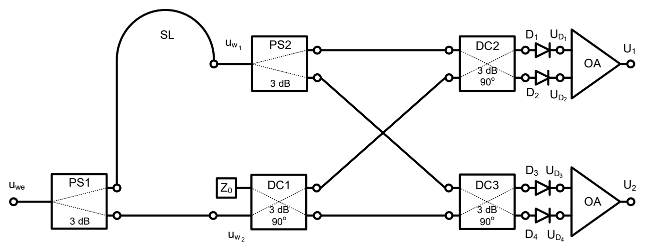

Fig. 4 Block diagram of microwave frequency discriminator that uses classic interferometer structure.

Submission of U_1 and U_2 allows the elimination of amplitudes and obtaining the tangent of the angle by which the signal will be delayed passing through the SL line. Therefore, to determine the frequency of the input signal, the equation 31 should be used:

$$f = \frac{(arc\ \tan(\frac{U_1}{U_2}))\cdot v}{2\cdot\pi\cdot l_{SL}} \quad (31)$$

for

$$l_{SL} = \frac{v}{f_g - f_d} \quad (32)$$

where: f_g – upper pass band frequency;
f_d – lower pass band frequency.

For the DIFM purposes the U_1 and U_2 analogue values presented as charts in figure 5 are converted to digital value (B_{U_1} and B_{U_2} respectively) of "0" for the frequency band where it is negative value or "1" for the frequency band where it is positive value and to binary code value$_C$ eventually.

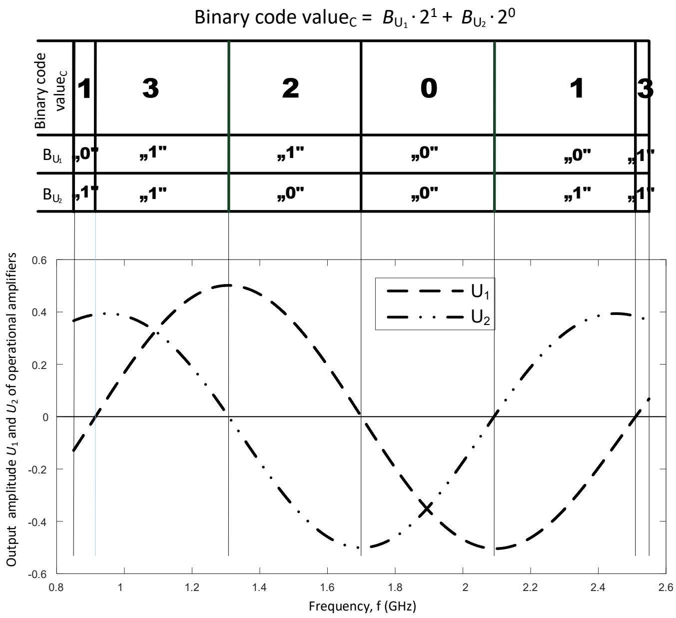

Fig. 5 Conversion of the U_1 and U_2 to digital value and to binary code value$_C$

As it can be noticed in figure 5 there are two pairs of subbands where are assigned the same binary code values$_C$ (value 1 and 3). It shows that under these conditions the frequency measurement is ambiguous.

IV. Operation of Frequency Discriminator Based on 4 x 4 Butler Matrix Type Microwave Interferometer

In this paper, the 4 × 4 Butler Matrix [8, 9] built of four DC quadrature couplers and two broadband phase shifters PF is used as the interferometer of the microwave phase detector (Fig. 6) [10].

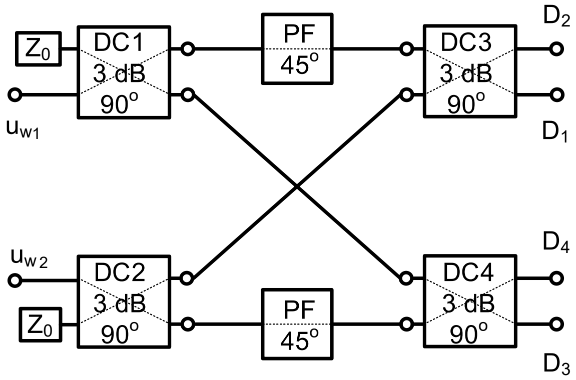

Fig. 6. Block diagram of interferometer of 4 x 4 Butler Matrix structure.

For input signals:

$$u_{w_1} = U_{w_1} \cdot \sin(\omega \cdot t + \varphi_{w_1}) \quad (33)$$

and accordingly:

$$u_{w_2} = U_{w_2} \cdot sin(\omega \cdot t + \varphi_{w_2}) \quad (34)$$

We can described output signals similar to classic structure interferometer:

$$u_{D_1} = T_{1w_1} \cdot u_{w_1} + T_{1w_2} \cdot u_{w_2} \quad (35)$$

$$u_{D_2} = T_{2w_1} \cdot u_{w_1} + T_{2w_2} \cdot u_{w_2} \quad (36)$$

$$u_{D_3} = T_{3w_1} \cdot u_{w_1} + T_{3w_2} \cdot u_{w_2} \quad (37)$$

$$u_{D_4} = T_{4w_1} \cdot u_{w_1} + T_{4w_2} \cdot u_{w_2} \quad (38)$$

But this time, due to different structure of interferometer, the coefficients describing the signal paths from the input to outputs will be represented by the following expressions:

$$T_{1w_1} = S_{D_1} \cdot S_{PF_1} \cdot S_{D_3} \quad (39)$$

$$T_{2w_1} = S_{D_1} \cdot S_{PF_1} \cdot S_{C_3} \quad (40)$$

$$T_{3w_1} = S_{C_1} \cdot S_{D_4} \quad (41)$$

$$T_{4w_1} = S_{C_1} \cdot S_{C_4} \quad (42)$$

and

$$T_{1w_2} = S_{C_2} \cdot S_C \quad (43)$$

$$T_{2w_2} = S_C \cdot S_{D_3} \quad (44)$$

$$T_{3w_2} = S_{D_2} \cdot S_{PF_2} \cdot S_{C_4} \quad (45)$$

$$T_{4w_2} = S_D \cdot S_{PF_2} \cdot S_{D_4} \quad (46)$$

where: S_D and S_C stands for direct and coupled transmittance of coupler, respectively.

$$u_{D_1} = \frac{1}{2} \cdot e^{j\cdot(-\frac{5}{4}\pi)} \cdot U_{w_1} \cdot e^{j(\omega t+\varphi_{w_1})} + \frac{1}{2} \cdot U_{w_2} \cdot e^{j(\omega t+\varphi_{w_2})} \quad (47)$$

$$u_{D_2} = \frac{1}{2} \cdot e^{j\cdot(-\frac{3}{4}\pi)} \cdot U_{w_1} \cdot e^{j(\omega t+\varphi_{w_1})} + \frac{1}{2} \cdot e^{j\cdot(-\frac{\pi}{2})} \cdot U_{w_2} \cdot e^{j(\omega t+\varphi_{w_2})} \quad (48)$$

$$u_{D_3} = \frac{1}{2} \cdot e^{j\cdot(-\frac{\pi}{2})} \cdot U_{w_1} \cdot e^{j(\omega t+\varphi_{w_1})} + \frac{1}{2} \cdot e^{j\cdot(-\frac{3}{4}\pi)} \cdot U_{w_2} \cdot e^{j(\omega t+\varphi_{w_2})} \quad (49)$$

$$u_{D_4} = \frac{1}{2} \cdot U_{w_1} \cdot e^{j(\omega t+\varphi_{w_1})} + \frac{1}{2} \cdot e^{j\cdot(-\frac{5}{4}\pi)} \cdot U_{w_2} \cdot e^{j(\omega t+\varphi_{w_2})} \quad (50)$$

After the amplitude square detection and filtering out the high-frequency component, voltages are obtained:

$$U_{D_1} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 - k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2} - \frac{\pi}{4}) \quad (51)$$

$$U_{D_2} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 + k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \cos(\varphi_{w_1} - \varphi_{w_2} - \frac{\pi}{4}) \quad (52)$$

$$U_{D_3} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 - k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \sin(\varphi_{w_1} - \varphi_{w_2} - \frac{\pi}{4}) \quad (53)$$

$$U_{D_4} = k_d \cdot \frac{1}{4} \cdot U_{w_1}^2 + k_d \cdot \frac{1}{4} \cdot U_{w_2}^2 + k_d \cdot \frac{1}{2} \cdot U_{w_1} \cdot U_{w_2} \cdot \sin(\varphi_{w_1} - \varphi_{w_2} - \frac{\pi}{4}) \quad (54)$$

where: k_d stands for proportionality factor (detection constant).

The system implementing described above operations is shown in the figure 7.

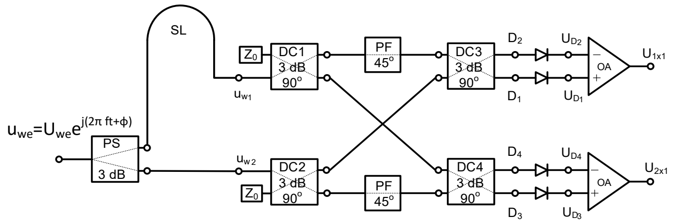

Fig. 7. Block diagram of microwave frequency discriminator that uses Butler Matrix 4 x 4 structure.

For such system, operation of summation properly selected pairs of detectors amplitudes by operational amplifiers gives two amplitudes which in their shapes are similar to sine and cosine functions (charts in Fig. 8).

Submission of U_{1x1} and U_{2x1} allows the elimination of amplitudes and obtaining the tangent of the angle by which the signal will be delayed passing through the SL line. Therefore, to determine the frequency of the input signal, the equation should be used [10]:

$$f = \frac{(arc\ \tan\left(\frac{U_{1x1}}{U_{2x1}}\right)+\frac{\pi}{4})\cdot v}{2\cdot\pi\cdot l_{SL}} \quad (55)$$

$$l_{SL} = \frac{v}{\mathrm{f}_g - \mathrm{f}_d}. \quad (56)$$

For the DIFM purposes the U_{1x1} and U_{2x1} analogue values presented as charts in Fig. 2 are converted to digital value ($B_{U_{1x1}}$and $B_{U_{2x1}}$ respectively) of "0" for the frequency band where it is negative value or "1" for the frequency band where it is positive value and to binary code value$_B$ eventually.

Binary code value$_B$ = $B_{U_{1x1}} \cdot 2^1 + B_{U_{2x1}} \cdot 2^0$

Binary code value$_B$	2	0	1	3	2
$B_{U_{1x1}}$	„1"	„0"	„0"	„1"	„1"
$B_{U_{2x1}}$	„0"	„0"	„1"	„1"	„0"

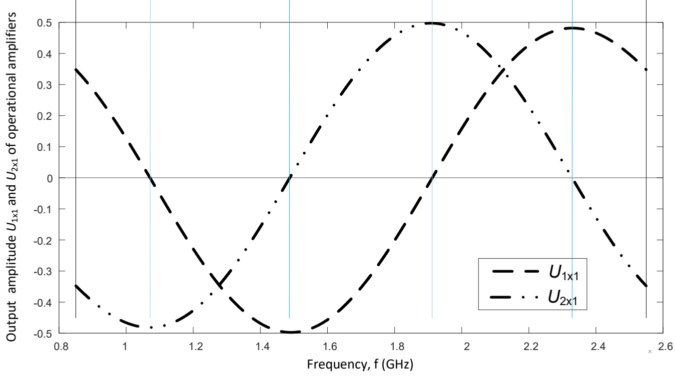

Fig. 8. Process of converting analogue values of operational amplifiers voltage signals to binary code value$_B$.

As it can be noticed in the Butler Matrix version of microwave interferometer cannot be possible to unequivocal distinguish frequency subbands too. However appropriate method may be used that in the consequence ambiguity of frequency subbands discrimination will be solved.

For this purpose an another - disambiguating signal U_{UxKL} must be worked out (3).

$$U_{\mathrm{UxKL}} = a \cdot U_{1\mathrm{xM}} + b \cdot U_{2\mathrm{xN}} \tag{57}$$

where:

- $U_{1\mathrm{xM}}$, sine signal $(U_{\mathrm{D}_1} - U_{\mathrm{D}_2})$ from system with $M \cdot SL$ length line, for M=1, 4, 16…,
- $U_{2\mathrm{xN}}$, cosine signal $(U_{\mathrm{D}_3} - U_{\mathrm{D}_4})$ from system with $N \cdot SL$ length line for N=1, 4, 16…,
- a, b – coefficients that decide about of math operation sign, $a \in \{-1, 1\}$ and $b \in \{-1, 1\}$
- U_{UxKL}, disambiguating signal for system with $L \cdot SL$ length line, for L=1, 4, 16…, and:

$$\begin{array}{llll} K = 1 & \text{for} \quad a = -1 & \text{and} & b = -1 \\ K = 2 & \text{for} \quad a = -1 & \text{and} & b = 1 \\ K = 3 & \text{for} \quad a = 1 & \text{and} & b = -1 \\ K = 4 & \text{for} \quad a = 1 & \text{and} & b = 1. \end{array}$$

Naturally, in the next step, this signal U_{UxKL} have to be converted to binary code value - $B_{\mathrm{U_{UxKL}}}$ as well.

For this particular case disambiguating signal is going to be $B_{\mathrm{U_{Ux41}}}$ (*SUM* signal), what means that it will be combination of two $U_{1\mathrm{x}1}$ and $U_{2\mathrm{x}1}$ output amplitude – the digital value of sum of this two (Fig. 9).

Binary code value$_B$ = $SUM \cdot 2^2 + B_{U_{1x1}} \cdot 2^1 + B_{U_{2x1}} \cdot 2^0$

Binary code value$_B$	2	0	1	5	7	6
SUM	„0"	„0"	„0"	„1"	„1"	„1"
B_{Ux1}	„1"	„0"	„0"	„0"	„1"	„1"
B_{Ux1}	„0"	„0"	„1"	„1"	„1"	„0"

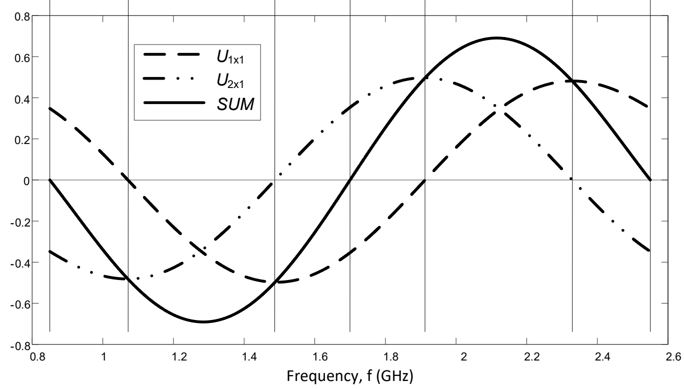

Fig. 9. Process of converting analogue values of operational amplifiers voltage signals and SUM signal to binary code value$_B$

This quite simple operation – which requires adding the sum operation element (Fig. 10), already existing signals, $U_{1\mathrm{x}1}$ and $U_{2\mathrm{x}1}$, will distinguish unambiguously frequency subbands in the whole operating band of MDF.

Six subbands for one discriminator (with one delay line) and three output signals: $U_{1\mathrm{x}1}$ and $U_{2\mathrm{x}1}$ and *SUM* signal.

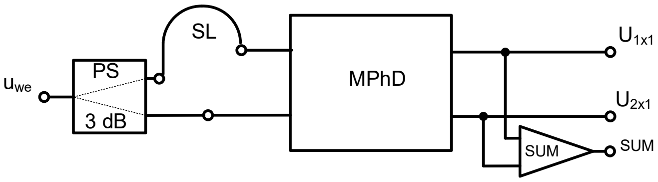

Fig. 10. Block diagram of microwave frequency discriminator with SUM signal.

For the purpose of increasing accuracy of discriminator in the way of narrowing down the unequivocal frequency bands it seems logical to add another discriminator which unambiguous frequency bandwidth will match to bandwidth of four previous subbands. This operation will required to manufacture delay line which length will be appropriate for such discriminator – which physical length will be four times longer in comparison to previous device (Fig. 11).

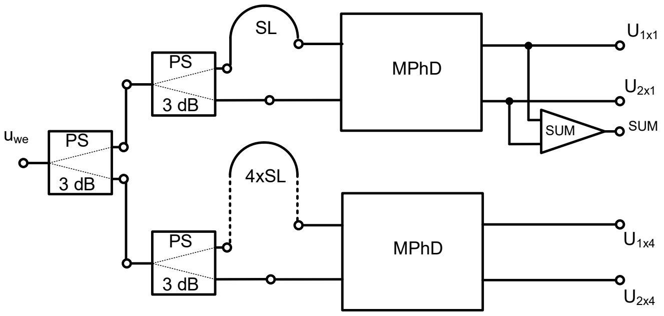

Fig. 11. Block diagram of two track microwave frequency discriminator with *SUM* signal.

This kind of double track discriminator will provide additional digital value signals $U_{1\mathrm{x}4}$ and $U_{2\mathrm{x}4}$ as is shown in figure 11. It can be noticed that there is more subbands (13) – narrowed ones, but at the same time it must be raised that two pairs of ambiguous subbands have arisen. Subband with binary code value "8" and subband with binary code value "15".

So again, even for such – double track discriminator, cannot be possible to unequivocal distinguish frequency subbands too. But, again another signal (sixth one) may be used to tackle the problem of frequency ambiguity.

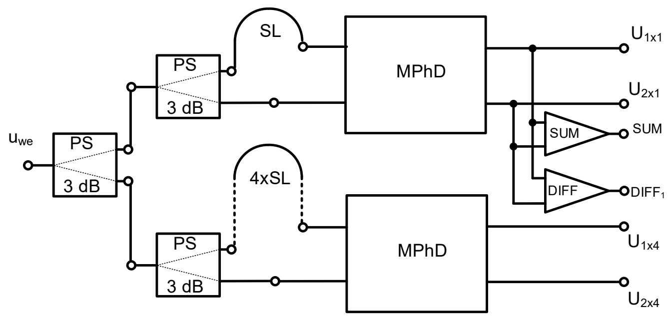

Fig. 12. Block diagram of two track microwave frequency with *SUM* and *DIFF*$_1$ signals

For this purpose the signal $B_{U_{Ux31}}$ ($DIFF_1$ signal) - difference of U_{1x1} and U_{2x1} must be worked out (Fig. 12). So the new binary code value of the double track discriminator (inclusive the binary value of $DIFF_1$ signal) subbands will distinguish all subbands unequivocally.

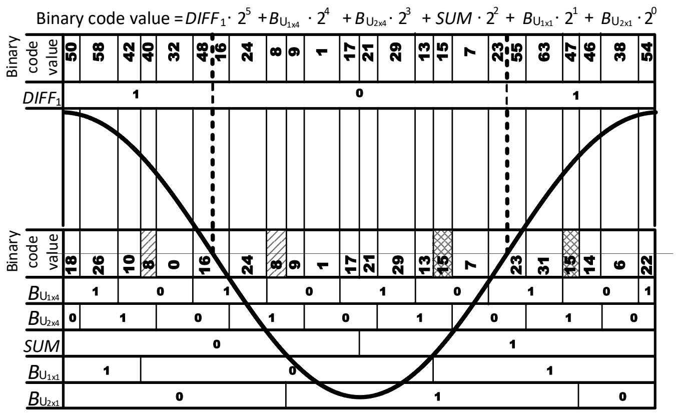

Fig. 13. Ambiguity removal double track MFD by using a difference signal (DIFF1).

Going further, it has been proved that the use of another track with applied delay line with physical length sixteen times longer in comparison to line at first track (which provide U_{1x16} and U_{2x16} output amplitude) will increase accuracy of discriminator in the way of narrowing down – increasing the number of the frequency bands. Having signals U_{1x1}, U_{2x1}, SUM ($B_{U_{Ux41}}$), U_{1x4}, U_{2x4}, $DIFF_1$ ($B_{U_{Ux31}}$), U_{1x16}, U_{2x16} and $DIFF_4$ ($B_{U_{Ux34}}$), where $DIFF_4$ – is the difference of U_{1x4} and U_{2x4}, it is possible to get 96 different unequivocal frequency subbands. It is worth to point out, that to solve the problem of frequency ambiguity the particular track for systems with delay line equal to multiply SL lengths, the use of sine and cosine signal from the track step back (from track with line four time shorter) is sufficient.

MDF track equipped with shorter delay line will work for a coarse discrimination and MDF track equipped with longer delay line will work for fine discrimination.

V. Conclusion

Microwave frequency discriminators (MFD) system which signals are digitized are very useful when it comes to achieving results in a matter of time. Unfortunately, because the real elements with real characteristics are used its creates situations that in a wide band there will be ambiguity subbands.

In the paper it was point out that using the 4 × 4 Butler Matrix as the interferometer of the microwave phase detector create new possibilities. The system that is characterized by symmetry when it comes to the structure, pose the opportunity to remove in the simple way the ambiguity of the discriminated frequency bands, despite the use of elements whose characteristics are not idealized. This goal is achieved by working out additional signals that are obtained by adding or subtracting the signals already existing. This method of ambiguity removal is very promising even for high accuracy systems consisting of multiple tracks working with lines of different but specific lengths.

References

[1] Stec B. (1980). Broadband homodyne system for measuring microwave circuits. Proceedings of the MESC, Gdańsk (in Polish).

[2] [2] Stec B. (1985). Microwave phase discriminator. Bulletin Military University of Technology vol. 392, Warszawa, (in Polish).

[3] [3] Smólski B. (1980). Analysis and synthesis of instantaneous frequency measurement systems. The Supplement to the Bulletin of Military University of Technology No. 8, Warszawa (in Polish).

[4] [4] Rutkowski A., Stec B. (1998). A Planar Microwave Frequency Discriminator. Proceedings of the 12th International Conference on Microwaves and Radar, MIKON-98, (IEEE Cat. No.98EX195), Kraków. https://doi.org/10.1109/MIKON.1998.740805

[5] East P.W. (2012). Fifty years of instantaneous frequency measurement. IET Radar, Sonar & Navigation Vol. 6, Issue 2, 2012, pp. 112–122. https://doi.org/10.1049/iet-rsn.2011.0177

[6] Rutkowski A. (1990). Analysis of microwave phase and frequency discriminators with analog and digital processing of output voltages. [Doctoral dissertation, Military University of Technology, Warszawa] (in Polish).

[7] Stec B., Rećko C. (2006). Ambiguity in determining the frequency of the ring frequency discriminator. Bulletin Military University of Technology, No. 1, Warszawa (in Polish)

[8] Wincza K., Gruszczyński S. (2012). Miniaturized Broadband 4 x 4 Butler Matrix Designed with the Use of Quasi-Lumped Coupled-Line Couplers. 8th International Caribbean Conference on Devices, Circuits and Systems (ICCDCS). Playa del Carmen, Mexico. https://doi.org/10.1109/MRRS.2011.6053615

[9] Wincza K., Gruszczyński S., Sachse K. (2011). Ultrabroadband 4 x 4 Butler Matrix with the Use of Multisection Coupled-line Directional Couplers and Phase Shifters. Microwaves, Radar And Remote Sensing Symposium. Kiev, Ukraine. https://doi.org/10.1109/MRRS.2011.6053615

[10] Stadnik H., Stec B. (2020). Microwave frequency detector using a 4x4 Butler matrix. SPIE Proceedings Volume 11442, USA. https://doi.org/10.1117/12.2565293