A sub-THz Mach-Zehnder quadruplexer

L.Lubyako [1*] and W. A. Bongers [2]
[1] Institute of Applied Physics RAS, 603950, Nizhny Novgorod, Russia,
[2] DIFFER (Dutch Institute For Fundamental Energy Research). PO Box 1207, 3430 BE Nieuwedein, The Netherlands W.A.Bongers@differ.nl
[*1] E-mail: lub@appl.sci-nnov.ru

(Received January 09, 2012)

Abstract: The paper describes a multi-port, multi-frequency, quasi-optical device capable to combine four incident waves and to switch the combined wave flow from one output channel to another by control of input wave frequencies.

Keywords: Quasi-optic, Diplexer, Mach-Zehnder interferometer.

doi: 10.11906/TST.183-188.2013.09.12

1. Introduction

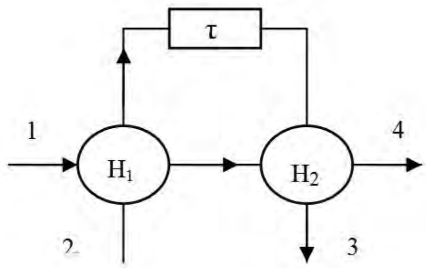
Multiplexers [1] are known to be used

- to combine and switch waves different in frequencies due to the reciprocity principle,
- to distribute waves of different frequencies between different outputs.

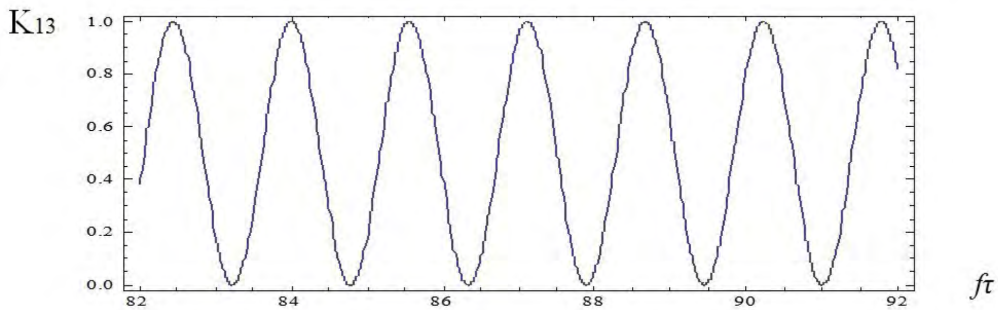
Among applications of multiplexers, there are microwave communication, radar and, at the present time, the fusion plasma stabilization [1-4]. This paper presents an elementary theory and a simplest experiment with a quasi-optical quadruplexer based on Mach-Zehnder cells.

2. The Elementary mach-zehnder interferometer performance

The usual Mach-Zehnder interferometer (Fig.1a) consists of two 3-*dB* hybrids and two different channels between them. The wave incident to any input 1 or 2 is split by the first hybrid into two equal power waves.



(a)



(b)

Fig.1 a) Scheme of Mach-Zehnder interferometer: H_1, H_2 – hybrids, τ – time delay due to channels length difference. b) Transmission coefficient from inputs 1 to output 3 of 140 *GHz* band interferometer with fix delay $\tau = 6.2\text{Ч}10^{-10}$ *c*.

These waves, after propagation through the channels of different lengths with the delay time difference τ, are combined by the second hybrid. In the ideal case, the wave transmission coefficients $K_{i,j}$ (Fig. 1b) represent the following functions of the wave frequency f :

$$K_{13} = \cos^2 \pi f \tau \,, \quad K_{23} = \sin^2 \pi f \tau \qquad (1)$$
$$K_{14} = \sin^2 \pi f \tau \,, \quad K_{24} = \cos^2 \pi f \tau$$

To combine two signals with different frequencies f_1 and f_2, the minimal delay time is $\tau_1 = 1/2(f_2 - f_1)$. However, according to (1) and Fig. 1, the wave combining may be provided at longer delay times as well. This effect may be used to make multiplexers composed of Mach-Zehnder cells.

3. A Quadroplexer theory

Four waves of different frequencies may be combined (Fig. 2) by successive stages:

- waves of frequencies f_1 and f_2 are combined by the interferometer “A”, and waves of frequencies f_3 and f_4 are combined by the interferometer “B”;

- the pairs of combined waves are delivered, with frequency switching, to inputs of the interferometers “C” and “D”;

- with frequency switching, the total power may be delivered to any of outputs 1-4.

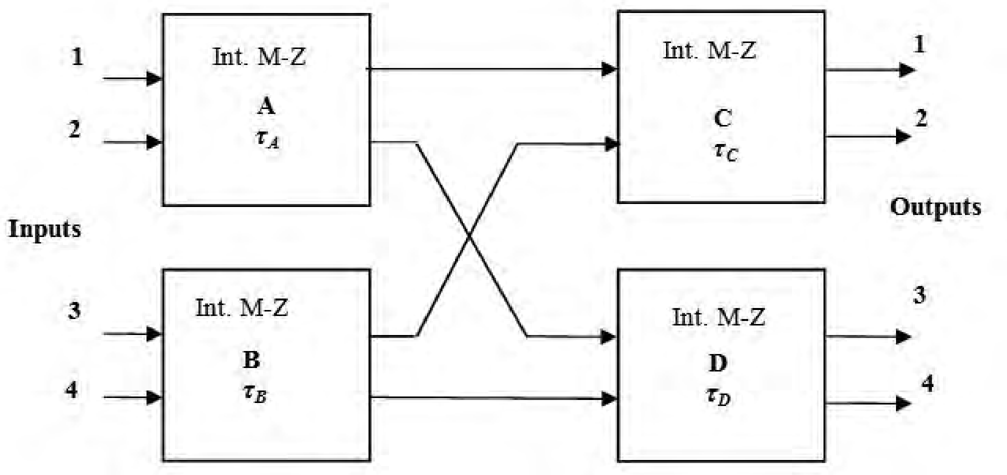


Fig. 2 The scheme of quadruplexer.

Transmission coefficients of this quadroplexer represent multiplications of the frequency controlled transmission coefficients of the first and the second stages:

$$K_{11} = \cos^2 \pi f_1 \tau_A \cos^2 \pi f_1 \tau_C = 1 \quad (2)$$
$$K_{21} = \sin^2 \pi f_2 \tau_A \cos^2 \pi f_2 \tau_C = 1 \quad (2)$$
$$K_{31} = \cos^2 \pi f_3 \tau_B \sin^2 \pi f_3 \tau_C = 1$$
$$K_{41} = \sin^2 \pi f_4 \tau_B \sin^2 \pi_4 f \tau_C = 1$$

According to (2), waves of frequencies f_1 and f_2 and waves of frequencies f_3 and f_4 are delivered to any of outputs 1-4, if the last stage delay time is $\tau_C = 1/2(f_3 - f_1) = 1/(f_2 - f_1) = 2\,\tau_A$. As an example, the Fig. 5 shows wave transmission functions calculated for one of the outputs of a quadruplexer designed to operate at 140 *GHz.*

4. Modeling experiment at 140 *GHz*

The quadroplexer performance was experimentally simulated at a mock-up (Fig.3) which scheme was reduced and inverted relative to that shown in Fig. 2. The mock-up was composed of

1) A 140 *GHz* source – a BWO phase-locked to a quartz-based source;

2) Three Mach-Zehnder interferometers (A, B and C);

3) Two RF detectors D1 and D2;

4) 0 - 50 *dB* tunable attenuator (Att.1);

5) A quasi-optical attenuator (Att.2) to exclude resonances at spurious modes.

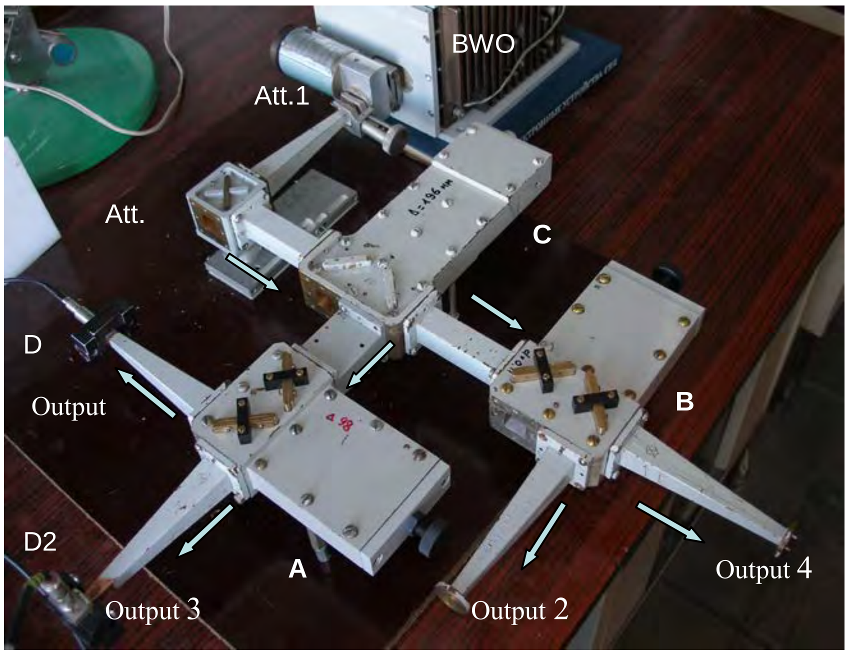


Fig. 3 The 140 *GHz* quadroplexer mock-up.

The interferometers A, B and C [5, 6] were composed of oversized square-cross-section waveguides and mica plate 3*dB* splitters. The oversized waveguides were coupled to single mode waveguides with pyramidal adapters. The output voltages of detectors were measured with digital voltmeters. The setup was preliminarily adjusted by tuning delay lengths of interferometers: in accordance to (2) the condition $\tau_C = 2\tau_A$ at f_0 = 140 *GHz* and $\tau_C = 2\tau_B$ at f_1 = 140.8 *GHz* were satisfied.

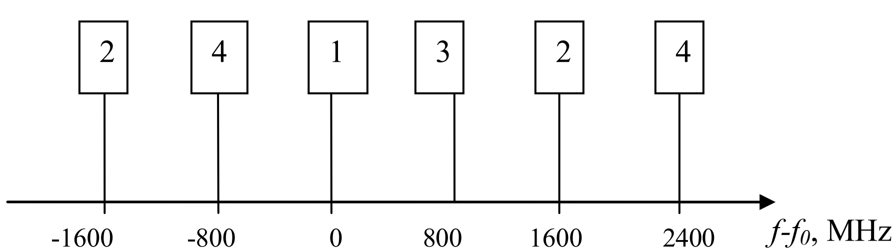


Fig 4. Frequencies of total RF power transmission to one of outputs.

The BWO signal was fed to the interferometer C (Fig. 3). The signal was switched between two outputs of the interferometer C by changing the BWO frequency at Δf_1 = 800 *MHz*. The outputs of interferometer C were connected to interferometers A and B. By changing the frequency at Δf_2 = 1600 *MHz*, the interferometer A switched the signal between outputs 1 and 3. The interferometer B performed the similar function: switching the signal between outputs 2 and 4. Thus, in accordance to (2), the quadruplexer transmitted the whole RF power ($K_{ij}=1$) to one of 4 outputs at discreet frequencies shown in Fig. 4.

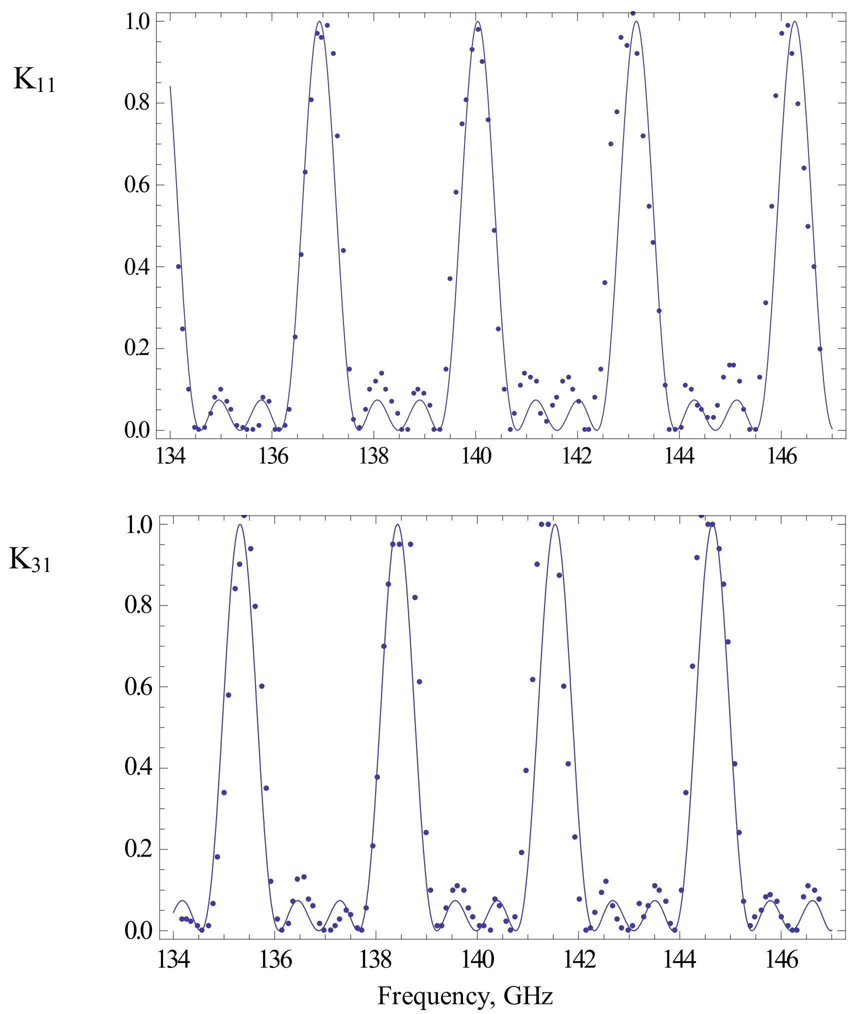


Fig. 5 The quadroplexer transmission functions for two outputs: solid curve – calculation, dots – experimental data.

In the experiment (Fig.5), the frequency was changed discretely by 100 *MHz* steps within 134-148 *GHz* interval (the bandwidth was limited with characteristics of the splitting plates of interferometers). The band included 16 frequency channels, each of 0.7 *GHz* bandwidth at the 3 *dB* level.

5. Summary

Thus, the above theory and experiment proved to be in a good mutual agreement. Though our experimental mock-up (Fig. 3) realized only a part of the scheme shown in Fig. 2, there is no doubt that a quadruplexer assembled in accordance to the full Fig. 2 scheme would operate as well. Moreover, the method based on using Mach-Zehnder interferometers may be expanded to combining/separating and switching of still larger amounts of partial wave beams. Of course, for high RF power applications [7, 8], all components of such devices should be efficiently cooled and should provide efficient out-filtering of spurious modes.

This work is supported by the grant of RFBR 11-02-00554 and the grant 047.018.002, Centre of Excellence, the Nederland. The authors are grateful to Michael Petelin for constructive discussions.

References

1. W. Kasparek, M. Petelin, V. Erckmann, et.al. "High-power microwave diplexers for advanced ECRH systems". *Fusion Engineering and Design*, 84, 1002-1005 (2009).

2. V. Erckmann, W. Kasparek, Y. Koshurinov, et.al. "Power Combination of two 140 *GHz* Gyrotrons and Fast Switching of the Combined Beam". *Fusion Sci. Technol*. 55, 23-30 (2009).

3. J.M. Usoff. "Haystack Ultra-wideband Satellite Radar (HUSIR)". *Boston*, IEEE (2007)

4. Petelin M.I., Garyotakis G., Tolkachev A.A. et al. *Proc. Amer. Institute of Physics Conf.* 474. N.Y.: Woodbury,. 304(1998)

5. L.I. Fedoseyev and Yu.Yu.Kulikov. "Super heterodyne radiometers for the millimeter and submillimeter bands". *Radio Eng. And Electron Phys.*, 16, 637-641 (1971).

6. Yu. Dryagin, L.Kukin and L.Lubyako, *Radio Eng. And Electron Phys.*, 19, 8, 1779-1780 (1974).

7. W. Wubie et al.. "Numerical and experimental investigations of a diplexer for combination and switching of high-power millimeter waves". *Int. Conf. on Infrared and Millimeter Waves, Pasadena* (2008).

8. W. A. Bongers, A. P. H. Goede, et al.. "Magnetic Island Localization for NTM Control by ECE Viewed Along the Same Optical Path of the ECCD Beam". Fus. Sci. Techn., 55, 2, 188-203 (2009).