New functionality in microwave interferometry by application of metastructure as a tunable beam-splitter

G Kraftmakher *, V Butylkin, Y Kazantsev and V Mal'tsev
Kotelnikov Institute of Radioengineering & Electronics RAS (Fryazino Branch),
Fryazino, Moscow Region, 141190, Russia
* gkraft@ms.ire.rssi.ru

Abstract. A new functionality of microwave interferometry is demonstrated by application of metastructure, meta-surface or meta-atom as controlled original beam-splitter in modified interferometer on basis of $h$-plane waveguide tee. Specific selectively-tunable interference peaks are observed in transmission of microwaves due to influence of metastructure properties on shape, frequency and intensity of interference peak, when controlled structure resonance approaches interference peak. We investigated following structures as a beam-splitter: ferrite plate, individual conductive resonant element in the form of varactor-loaded butterfly dipole, and metastructure wire grating/varactor-loaded copper strip placed orthogonally. The obtained results open new possibilities to design microwave multifarious multiband spectral filtering and implement selective electric or magnetic tuning, required in multifunctional and multichannel wireless communication.

1. Introduction
At present microwave tunable multiband spectral filters, required in multifunctional wireless communication, are subjects of great interest [1]. They play important role for channel selection and signal processing. Basis of the microwave multiband filter is a cascade of different resonators in combination with transmission line. To select required filter electromechanical or electrical switch by varactor diodes is usually used. But it is very difficult to achieve both tunable and multiband spectral filtering [2]. We propose to implement tunable microwave multiband filtering through modified interferometer on basis of rectangular waveguide tee named as “meta-interferometer” [3], in which a metastructure ferrite plate/varactor-loaded dipole or ring conductive elements [4, 5] is embedded as magnetically and electrically controlled beam-splitter. Metastructures containing double split-ring resonators, chiral spirals, omega particles [6], coupled nonlinear resonators [7] can be also compatible with control elements and used as beam-splitters. Here we present measurement results of electromagnetic waves transmission coefficient $T$ in meta-interferometer with ferrite plate, varactor-loaded butterfly dipole, and metastructure wire grating/varactor-loaded copper strip at $3 – 6$ GHz in dependence on magnetostatic field $H$ or voltage $V_{DC}$.

2. Proposed meta-interferometer
Empty rectangular waveguide $h$-plane tee (Port 1 is input) is transformed into interferometer and acts as multiband filter in frequency dependence of transmission in the cases when Port 2 (or 3) is short
circuited. In order to increase a number of interference bands it is necessary to increase a length of short circuited Arm. Meta-interferometer, Figure 1(a), contains addition: tunable beam-splitter, Figure 1 (b, c, d). Short circuited side $h$-Arm (24x48 mm) has length 250 mm and is removable. For tuning we use varactor MA46H120 (MACOM), with capacitance varying from 1 to 0.15 pF by supplying back bias voltage $V_{be}$ from 0 to 10 V. Varactor is welded into the gap of resonant elements. The sizes of elements are chosen so that the resonance response of transmission coefficient $T$ will be observed at frequency in the given range 3–6 GHz of the voltage standing wave ratio (VSWR) panoramic measurer.

![Image](image.png)

**Figure 1.** Proposed meta-interferometer (a), and investigated beam-splitters containing (b) ferrite plate, (c) varactor-loaded butterfly dipole, and (d) metastructure wire grating/strip

Beam-splitter is placed along axis of main waveguide 1 across the side $h$-Arm. Meta-interferometer acquires new functionalities due to resonance properties of beam-splitter and superposition of transmitted, reflected and re-reflected waves. In this case periodicity violation, change of shape and position of interference bands and possibility of multifarious control is observed in dependence on resonance properties of beam-splitter (width, intensity and frequency of the resonance).

3. Main experimental results

3.1. Ferrite plate as a beam-splitter. Figure 2 shows results of measurements of transmission coefficients $T$ in meta-interferometer with ferrite plate (21x14x2 mm) of yttrium-ferrum garnet at different $H$. Under $H = 0$ one can see narrow stop-bands $F_i$ and wide pass-bands. Ferromagnetic resonance (FMR) is excited in the presence of $H$-field and shifts to higher frequencies with the increase in $H$-field magnitude and exerts influence on the interferogram. The FMR and stop-bands $F_i$ are getting nonreciprocal as it is difference $\delta T = T(H^-) - T(H^+)$ between $T$ corresponding to the opposite directions of magnetization at $H^-$ and $H^+$. The $F_i$ nonreciprocity $\delta T (F_i)$ increases when the FMR approaches. Sign of $\delta T$ depends on position of the FMR about the $F_i$ and can be changed under small variation of $H$-field value. For example, $\delta T (F_1)$ is positive at 740 Oe and is getting negative at 780 Oe. The FMR can exert influence on each stop-band by turns with $H$-field increase.
3.2. Varactor-loaded butterfly dipole (22x10 mm) as a beam-splitter. In Figure 3(a, b) one can see that meta-interferometer shows multiband spectral filtering, different from five-band spectrum of empty interferometer (EI). We see also in Figure 3(c) typical resonance dependencies of $T$ (dipole resonance DR) in rectangular waveguide (WG) by the application of a bias voltage $V_{DC}$ to varactor. In meta-interferometer pass-bands narrowing and stop-bands (F) widening is observed. Besides, meta-interferometer acquires new capability, such as selective specific control covering several interference bands because of influence of wide dipole resonance DR. In this case intensity, width and frequency ($f_i$) of different interference bands are controlled differently in dependence on DR position ($f_{DR}$).

Figure 2. Measured transmission $T$ in meta-interferometer with ferrite plate at $H^+ = H^- = 740$ and 780 Oe in comparison with $H = 0$

By variation of $V_{DC}$ from 0 V to 10 V increase of level and widening of pass-bands as well considerable narrowing and shifting of stop-bands occurs; at that different bands are tuned differently. Really, band $F_1$ (3.66 GHz) is not shifting, while bands $F_2$ (3.96 GHz); $F_3$ (4.38 GHz); and $F_4$ (4.78 GHz) shift to 4.14; 4.6 and 5.1 GHz on 0.18; 0.2 and 0.3 GHz and switch between stop- (-20; - 25 dB) and pass-bands (-5 dB) takes place.

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3.3. Metastructure wire grating/varactor-loaded copper strip, as a beam-splitter. Proposed beam-splitter is a periodical grating of cut-wires embedded into dielectric film (wire length $l = 18$ mm, thick of wire 0.1 mm, distance between wires is 0.2 mm) and varactor-loaded longitudinal copper strip (length $l_s = 25$ mm, width is about 1 mm) on 2 mm-thick textolite substrate, Figure 1(d). Grating shows resonance effect above given range 3-6 GHz. We suppose that microwave magnetic field $h$ near grating inducts electromotive forces and anti-parallel currents in many spatial $U$-circuits created from cut-wire pairs of a grating and section of longitudinal strip and like-directed currents along longitudinal strip. Contribution of total currents from $U$-circuits along varactor-loaded single longitudinal half-wavelength strip provides voltage-controlled resonance of strip, Figure 4(a) and possibility to exert influence on the interferogram, Figure 4(b). In the case when we use wire grating without strip, as a beam-splitter, stop-band reduction and level decrease is observed, Figure 4(c).

Losses in meta-interferometer with wire grating and metastructure wire grating/strip are less than with ferrite or dipole.

Figure 4. Measured transmission coefficient $T$ in (a) waveguide with a grating/strip, (b) meta-interferometer with a wire grating/strip, and (c) meta-interferometer with wire grating.

Conclusion
So, it has been proposed meta-interferometer in which selective magnetic or electric control of interferogram is achieved. Meta-interferometer is based on waveguide tee with ferrite plate, varactor-loaded butterfly dipole, or wire grating/strip, as an original tunable beam-splitter and shows specific selective magnetic or electric controllability of multiband spectral filtering at 3 – 6 GHz in dependence on tunable resonance properties of beam-splitter.

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References
[1] Cameron R, Kudsia C and Mansour R 2018 Microwave Filters for Communication Systems: Fundamentals, Design, and Applications (John Wiley & Sons)
[2] Fok M and Ge J 2017 Photonics 4 45
[3] Kraftmakher G, Butylkin V, Kazantsev Yu and Mal’tsev V 2019 JETP Letters 109 4 232
[4] Kraftmakher G, Butylkin V and Kazantsev Yu 2013 Tech. Phys. Letters 39 505
[5] Butylkin V, Kazantsev Yu, Kraftmakher G and Mal’tsev V 2017 Appl. Phys. A 123(1):57
[6] Tretyakov S 2017 J. Opt. 19 013002
[7] Dobrykh D A, Yulin AV, Slobozhanyuk A P, Poddubny A N and Kivshar Yu S 2018 Phys. Rev. Letters 121 163901