



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Vovchuk, Dmytro; Kosulnikov, Sergei; Simovski, Constantin Unusual eigenmodes of wire-medium endoscopes

Published in: Optics Express

DOI: 10.1364/OE.26.017988

Published: 09/07/2018

Document Version Publisher's PDF, also known as Version of record

Please cite the original version: Vovchuk, D., Kosulnikov, S., & Simovski, C. (2018). Unusual eigenmodes of wire-medium endoscopes: impact on transmission properties. *Optics Express*, *26*(14), 17988-18005. https://doi.org/10.1364/OE.26.017988

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.



# Unusual eigenmodes of wire-medium endoscopes: impact on transmission properties

DMYTRO VOVCHUK, 1,\* SERGEI KOSULNIKOV, 2 AND CONSTANTIN SIMOVSKI $^{2,3}$ 

<sup>1</sup>Department of Radio Engineering and Information Security, Yuriy Fedkovych Chernivtsi National University, 2, Kotsyubynsky Str., 58000, Chernivtsi, Ukraine

<sup>2</sup>Department of Metamaterials and Nanophotonics, ITMO University, Birzhevaya, 197043, St. Petersburg, Russia

<sup>3</sup>Department of Electronics and Nanoengineering, Aalto University, P.O. Box 15500, F100076, Aalto, Finland

\*dimavovchuk@gmail.com

**Abstract:** Wire-medium endoscopes represent a promising tool of THz sensing/imaging. Bending should not critically harm the endoscope operation and the issue of bending losses is that of key importance for any endoscope. In this paper we show that the frequency-averaged power transmittance of a wire-medium endoscope is weakly sensitive to the bending. However, the frequency dispersion of the power loss/transmittance of the endoscope is strongly oscillating. Frequency maxima of the loss factor result from unusual eigenmodes of an elongated wire medium sample. These modes comprise power vortices and their sensitivity to the sample bending seems to be a critical issue for the future of wire-medium endoscopes.

© 2018 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

OCIS codes: (160.3918) Metamaterials; (110.6795) Terahertz imaging; (300.6495) Spectroscopy, terahertz.

### **References and links**

- R. Kersting, H.-T. Chen, N. Karpowicz, and G. C. Cho, "Terahertz microscopy with submicrometre resolution," J. Opt. A 7(2), S184–S189 (2005).
- 2. P. Doradla, Terahertz Endoscopic System for Cancer Detection (Lambert Academic Publishing, 2015).
- W. L. Chan, J. Deibel, and D. M. Mittleman, "Imaging with terahertz radiation," Rep. Prog. Phys. 70(8), 1325–1379 (2007).
- A. Hassani, A. Dupuis, and M. Skorobogatiy, "Porous polymer fibers for low-loss Terahertz guiding," Opt. Express 16, 6341–6351 (2008).
- A. Hassani, A. Dupuis, and M. Skorobogatiy, "Low loss porous terahertz fibers containing multiple subwavelength holes," Appl. Phys. Lett. 92, 071101 (2008).
- K. Nielsen, H. K. Rasmussen, A. J. Adam, P. C. Planken, O. Bang, and P. U. Jepsen, "Bendable, low-loss Topas fibers for the terahertz frequency range," Opt. Express 17, 8592–8601 (2009).
- P. Doradla, C. Joseph, and R.H. Giles, "Terahertz endoscopic imaging for colorectal cancer detection: Current status and future perspectives," World J. Gastrointest. Endoscopy 9, 346–358 (2017).
- M. S. Vitiello, J. Xu, F. Beltram, A. Tredicucci, O. Mitrofanov, J. A. Harrington, H. E. Beere, and D. A. Ritchie, "Guiding a terahertz quantum cascade laser into a flexible silver-coated waveguide," J. Appl. Phys. 110, 063112 (2011).
- P. Doradla, C. S. Joseph, J. Kumar, and R. H. Giles, "Characterization of bending loss in hollow flexible terahertz waveguides," Opt. Express 20 (17), 19176–19184 (2012).
- A. Markov and M. Skorobogatiy, "Two-wire terahertz fibers with porous dielectric support," Opt. Express 21(10), 12728–12743 (2013).
- A. Tuniz, K. J. Kaltenecker, B. M. Fischer, M. Walther, S. C. Fleming, A. Argyros, and B. T. Kuhlmey, "Metamaterial fibres for subdiffraction imaging and focusing at terahertz frequencies over optically long distances," Nat. Commun. 4, 2706 (2013).
- 12. X. Radu, D. Garray, and C. Craeye, "Toward a wire medium endoscope for MRI imaging," Metamaterials **3**, 90–99 (2009).
- P. A. Belov, Y. Zhao, S. Tse, P. Ikonen, M. G. Silveirinha, C. R. Simovski, S. A. Tretyakov, Y. Hao, and C. Parini, "Transmission of images with subwavelength resolution to distances of several wavelengths in the microwave range," Phys. Rev. B 77, 193108 (2008).
- C. R. Simovski, P. A. Belov, A. V. Atrashchenko, and Yu. S. Kivshar, "Wire metamaterials: physics and applications," Adv. Mater. 24(31), 4229–4248 (2012).

https://doi.org/10.1364/OE.26.017988

Received 16 Apr 2018; revised 1 Jun 2018; accepted 1 Jun 2018; published 27 Jun 2018

- S. Kosulnikov, and C. Simovski, "On Fabry-Perot resonances of a wire-medium hyperlens," Photon. Nanostruct. Fundam. Appl. 15, 1–9 (2015).
- I. S. Nefedov and C. R. Simovski, "Giant radiation heat transfer through micron gaps," Phys. Rev. B 84(19), 195459 (2011).
- D. Vovchuk, S. Kosulnikov, I. Nefedov, S. Tretyakov, and C. Simovski, "Multi-mode broadband power transfer through a wire medium slab," Prog. Electromagn. Res. 154, 171–180 (2015).
- J. S. Brownless, B. C. P. Sturmberg, A. Argyros, B. T. Kuhlmey, and C. M. De Sterke, "Guided modes of a wire medium slab: comparison of effective medium approaches with exact calculations," Phys. Rev. B 91, 155427 (2015).
- K. J. Kaltenecker, A. Tuniz, S. C. Fleming, A. Argyros, B. T. Kuhlmey, M. Walther, and B. M. Fischer, "Ultrabroadband perfect imaging in terahertz wire media using single-cycle pulses," Optica 3(5), 458–464 (2016).

## 1. Introduction

Electromagnetic response of the majority of materials is especially strong in the THz range, that makes the THz sensing/imaging important for applications. A branch of the THz sensing/imaging based on the endoscopes, flexible and optically long THz waveguides, is promising for security, health and material science [1]. This technique comprises the detection/location of optically small objects, including subsurface ones, their spectroscopic analysis and imaging. For THz endoscopes the issue of losses is critical because the dissipative losses of materials are highest namely at THz frequencies and because the bending of the endoscope increases the losses. Therefore, the most part of conventional THz waveguides from hollow metal tubes to coplanar waveguides are unsuitable for the endoscopy [1–4]. Among already studied THz endoscopes the lowest transmission losses are manifested by porous plastic fibers (PPFs). A PPF comprises an array of longitudinal pores in the polymer fiber. PPFs exist in two variants – photonic-crystal fibers whose pores are regular and have the thickness of the order of hundred microns and effectively homogeneous PPFs whose pores have much lower diameters [4–6].

In order to prevent the guided mode leakage to (and its near-field coupling with) the ambient the thickness *D* of a usual PPF must be much larger than the wavelength  $\lambda$  [4,5]. Since at 0.3 THz  $\lambda = 1$  mm, it practically means  $D \gg 1$  mm. In fact, the condition  $D \gg 1$  mm implies that the radius *R* of curvature of the bent endoscope is much larger than 1 cm. Practically, for a PPF one needs  $R \ge 3$  cm [6,7]. The restriction origins from radiative losses which arise when the bending breaks the total internal reflection of the Brillouin waves i.e. destroys the confinement of the guided mode. This is a severe restriction because in many applications, especially in the medical ones, one needs to have an endoscope of thickness about 1 - 2 mm or thinner that can be introduced into a tiny hole e.g. into a needle of a syringe [1,7].

The miniaturization of a THz endoscopes is achievable in different ways. An endoscope of thickness 1 mm performed as a PPF with a thin flexible metal shield offers a deal between the losses in the metal and the mode confinement [7, 8]. However, bending losses of this thin endoscope are much higher than those of the usual cm-thick PPF with the same bending radius R because in the bent structure the electric field essentially penetrates into the metal shield [7, 8]. The same refers to hollow pipe waveguides with internal or external metalization of the flexible dielectric pipe [9]. Notice that in the shielded endoscopes the bending losses are dissipative ones.

Another type of an endoscope with enhanced confinement of the guided mode is a multiwire one. Here a PPF with effectively homogeneous cross section serves a low-loss dielectric matrix to a two-wire transmission line as in [10] or to an elongated sample of the wire medium as in [11]. In both cases the energy of the guided mode is almost completely concentrated between the wires and the electric field inside the metal constituent is relatively low. Such endoscopes possess acceptable dissipation per unit length at least when they are straight. In accordance to [10] the presence of two wires offers the miniaturization of the fiber diameter to 0.87 mm whereas the operation band extends to low frequencies down to 100 GHz. In this endoscope, the guided mode has a strongly subwavelength effective cross section (of the order of  $200 - 500 \,\mu$ m in the range 0.1 - 1 THz). The issue of bending losses for two-wire endoscopes has not been studied yet.

Wire-medium endoscope (WME) is an equidistant array of many parallel wires [11]. WMEs offer a novel functionality called instantaneous subwavelength imaging. The image is carried along the endoscope from the object to the receiver. The size of the imaged area is equal to endoscope width D and the spatial resolution corresponds the period a of the wire array. It is experimentally shown that an array of optically long and thin (dozens of  $\mu$ m) flexible wires in the PPF matrix is capable to transfer such the subwavelength image (image size 1.4 mm, resolution 0.2 mm) from one face of the WME to another face, whereas the near-field is spatiotemporally resolved at every point on this output plane via a raster scan. [11]. In fact, in [11] the wires of the endoscope were not exactly parallel but slightly divergent from the free endoscope face to its input face in order to make an array of wires spatially compatible with an array of THz detectors. In this way one obtained a magnified subwavelength image of an object located in front of the free face.

In the present paper we will not consider the imaging issues. We aim to study the impact of the endoscope bending to the losses. This issue, to our knowledge, has not been previously studied for THz endoscopes. In [12] one studied both transmission properties and subwavelength imaging, including the impact of the bending, for a WME used for magnetic resonance imaging (MRI). However, the results of this work are not applicable to THz endoscopes: the WME used in MRI applications is very short (its length *L* is of the order of  $\lambda/2$ ) and the frequency range is relatively narrow. In [12] the optical length of the endoscope varies in the limits  $(0.95 - 1.05)\lambda/2$ that does not give us the reliable information on the frequency-averaged bending losses.

Though the present study was motivated by the issue of bending losses for a WME, in this paper we extend our study beyond this initial task because the conventional concept of bending losses turned out to be irrelevant for WMEs. The bending drastically changes the power loss factor at every frequency, but the loss averaged over a broad frequency range increases very weakly and noticeable increase corresponds only to very small radius *R*. We have found that the transmissive and lossy properties of the WME are determined by the concurrence of the modes of two types. Modes of the first type are those of an infinite wire medium. Modes of the second type are specific to elongated samples of the wire medium. These modes comprise power vortices and correspond to high radiative losses even for straight endoscopes. Frequencies of these modes for a given length of the endoscope depend on *R*. It makes the narrow-band operation of the endoscope critically sensitive to the bending. Our theoretical results are validated by a modelling and microwave experiment.

## 2. Numerical study of a THz wire-medium endoscope

The structure of our WME of length L = 2 cm is shown in Fig. 1 for the case when the endoscope is bent uniformly and it forms a semicircle with the radius of curvature  $R = L/\pi \approx 6.3$  mm. Here and below we characterize the bent endoscope also by the bending angle  $\theta$  – in the present case  $\theta = 180^{\circ}$ . The PPF matrix of the wire array is formed by a polyethylene (dielectric constant  $\varepsilon = 2.25$ , absorption loss 180 dB/m in the range 0.1 - 1 THz) comprising longitudinal air holes of diameter  $d_{\rm h} = 200 \,\mu\text{m}$  arranged with the array period  $a = 250 \,\mu\text{m}$ . The WME cross section is square ( $D = 1.25 \,\text{mm}$ ). It comprises a regular array of  $6 \times 6$  copper wires of thickness  $d_{\rm w} = 40 \,\mu\text{m}$  arranged with the same period a.

In order to study the impact of bending to the power transmittance we calculated the transmission coefficient  $S_{21}$  for the system of two perfectly conducting dipoles of length  $l_d = 200 \,\mu\text{m}$  and thickness  $d_d = 40 \,\mu\text{m}$ . Dipole 1 (transmitting) and dipole 2 (receiving) are located exactly on two faces of our WME as it is shown in Fig. 1.

First, we have calculated the S-parameters of this system for two cases – the bent WME shown in Fig. 1 and its straight version. In the last simulations we assumed that the internal geometry of the straight WME was the same as that of the bent one. For the bent endoscope the length L = 2 cm refers to the central line connecting dipoles 1 and 2, and the lengths of the wires lie in



Fig. 1. A bent THz endoscope with a  $6 \times 6$  wire array in the PPF matrix. The source is emulated by dipole 1, fully similar to dipole 2, which is a receiving antenna.

the interval [17.9, 21.8] mm. For the straight endoscope all wires have the same length L = 2 cm. This difference between two WMEs is not relevant for their comparison, as it will be clarified below.

The S-parameters of the system were simulated using CST Studio Suite. In these simulations dipole 1 was fed by a lumped voltage generator with 50  $\Omega$  output and dipole 2 was loaded by 50  $\Omega$ . For the bent endoscope there is a difference between the horizontal (in the plane of the bend) and the vertical (orthogonal to this plane) orientations of the dipoles. Therefore, we have calculated the S-parameters for these two cases separately. We have checked that the cross-polarized transmittance of the WME is negligibly small as well as the transmittance between the parallel dipoles in absence of the endoscope ( $S_{21} < -200 \text{ dB}$ ). The resonance of our dipoles is strongly red-shifted by the presence of the endoscope and holds near 1.5 THz. In the range 0.5-1 THz the dipoles are optically short and their detuning from the resonance allowed us to detect the strong impact of the bending to the dipole matching.

In Fig. 2(a) the frequency dispersion of  $S_{21}$  for both straight and bent endoscopes is depicted. In general, this dispersion is strongly different from that obtained earlier for wire medium slabs (see e.g. in [13–15]). For a wire-medium slab one observes a regular set of narrow-band Fabry-Perot maxima separated by the equivalent frequency intervals where  $S_{21}$  is nearly uniform. In Fig. 2(a) we see a set of maxima and minima that can be identified with Fabry-Perot resonances. However, these resonances are relatively weak and do not explain sharp minima of the transmittance we observe on the plot. Frequencies of these minima (for the straight endoscope 0.56 THz, 0.69 THz, 0.87 THz) cannot be related to the length *L*.

The weakness of the Fabry-Perot resonances is not surprising. These resonances result from multiple internal reflections which are partially suppressed by the decay in our optically long endoscope. What is the physics of the deep minima of the transmittance if these are not Fabry-Perot minima?

If we average  $S_{21}$  calculated for the bent endoscope over two orientations of the dipole, the difference in  $S_{21}$  for the straight endoscope from that calculated for the bent one varies from +9 to -45 dB. Being averaged over the frequency range 0.5 - 1 THz this difference nearly equals



Fig. 2. (a) – Transmission coefficient  $S_{21}$  versus frequency for the straight and bent WMEs (mismatched dipoles). (b) – Reflection coefficient  $S_{11}$  versus frequency for the straight and bent WME. Two curves for the bent WME in both plots correspond to two orientations of the dipoles.

to  $\Delta S_{21} = -16$  dB. However, this difference does not imply the bending loss. In Fig. 2(b) we depict the dispersion of  $S_{11}$  for both straight and bent WMEs. One can see that bending the endoscope creates an overcritical mismatch for our short dipoles. This mismatch is the reason of the non-zero  $\Delta S_{21}$ . From the energy balance the power loss coefficient P of the endoscope can be calculated:  $P = 1 - S_{21}^2 - S_{11}^2$ . These calculations have shown that P averaged over the frequency range [0.5, 1] THz for the bent endoscope is not higher than that for the straight one (of the order of 0.5 in both cases). We do not show the frequency dispersion of *P* because we consider the result of these simulations as not very reliable one. In the regime of the strong mismatch even a small numerical error in the S-parameters results in a serious error for P. Since the optical length of our endoscope is huge S-parameters definitely accumulate a numerical error. We consider this result only as a hint that the concept of bending losses may be not directly applicable to a WME. It is also important that a rather slight bending of the WME results in a strong mismatch of the dipoles. Really, in the present case the radius of the WME curvature is optically large and we expected that our dipoles should have kept the same input impedance as they had for the straight WME. However, the input impedance of our dipoles changes drastically when they are applied on the bent endoscope. Bending results in the blue shift of the dipole resonance, and a similar



impact of bending was observed in work [12]. However, this effect in [12] was much weaker and was obtained for the case  $R < \lambda/2$ .



Fig. 3. (a) – A folded endoscope whose central part has a curvature of radius R = 1.025 mm. Internal radius of curvature  $R_1 = 0.4$  mm is subwavelength below 0.75 THz. (b) – Transmission coefficient  $S_{21}$  versus frequency for the straight and folded WMEs (mismatched dipoles).

Unexpected results for *P* and dipole matching motivated us to perform the next numerical study. In this study we assumed that the same WME is still coupled to the same dipoles but now it is bent non-uniformly, namely it is folded as we show in Fig. 3(a). The central part of the WME with length 3.3 mm is bent with the same bending angle  $\theta = 180^{\circ}$  but now the radius of curvature is equal to  $R = R_1 + D/2 = 1.025$  mm, where  $R_1 = 0.4$  mm is the internal radius of the bending that is subwavelength at frequencies below 0.75 THz. One could expect a drastic growth of radiation losses for such the severely bent endoscope and a strong reflection of the guided mode from the bend. However, our simulations have shown no growth of the frequency-averaged loss factor and no noticeable reflected wave between the transmitting dipole and the bend. The frequency dispersion of  $S_{21}$  presented in Fig. 3(b) is qualitatively the same as  $S_{21}$  calculated for the straight endoscope. Again, the frequency-averaged decrease of transmittance  $\Delta S_{21} = 12$  dB for the folded endoscope results from the enhanced mismatch of the dipoles.

After this study we have understood that the eigenmodes of the WME excited by our dipole can be very different from the modes of an unbounded wire medium. There unusual modes which are lossy and very sensitive to the bending. Since the dipoles at the corresponding frequencies are coupled to these modes, their presence or absence in some frequency range may strongly influence the impedance of the dipoles in this range.

These guesses demanded a more detailed and reliable study. Our THz endoscope is not a suitable platform for such investigations. Each simulation of a so long endoscope is extremely time-consuming. Therefore, for our next numerical study we have designed a WME shorter by an order of magnitude. Also, in this new study we remove those time-consuming features of the initial THz structure which are not relevant for our purposes. Namely, we assume that the wires of our WME are perfectly conducting and their background is free space.

## 3. Numerical study of a model endoscope

Having in mind that for a lossless structure there is no difference in which frequency band the simulations are done, the present numerical study where our WME operates in the band [1, 2] GHz can be formulated in terms of the optical sizes. Frequencies 1 - 2 GHz and length of the wires L = 785 mm correspond to the optical lengths within  $kL \approx 14 - 28$ . Our array consists of  $7 \times 15$  wires of thickness  $d_w = 1$  mm, and the array period a = 10 mm. The cross section of the WME is now a rectangle  $80 \times 160$  mm.

Since the Fabry-Perot resonances in the WME are irrelevant and mask the unusual modes we aim to reveal the structure under study should be designed so that to suppress these resonances. It worth noticing that a significant though not complete suppression of the Fabry-Perot resonances for wire media slabs was achieved if the wire medium operated at infrared frequencies and was sandwiched between two dielectric half-spaces (see e.g. in [16]). The best suppression of the Fabry-Perot resonances corresponds to submerging the ends of the wires into the dielectric to a subwavelength small depth. Then at each of two interfaces of the wire-medium slab an effective transition layer was formed. In this transition layer the TM- and TE-polarized waves transformed into quasi-TEM modes of the infrared wire medium.

However, for our microwave WME this way of the broadband matching is not suitable and we have to find another method. In our work [17] we have damped the Fabry-Perot resonances of a wire-medium slab locating it in between two sections of a hollow metal waveguide. In fact, in work [17] we implemented the same idea of [16] replacing the surfaces of two dielectric media by the apertures of two waveguide sections. Inserting our wire medium sample to a small depth  $0 < d \ll \lambda$  into each of two waveguides we managed (theoretically and experimentally) to suppress the Fabry-Perot resonances and to match the sample in the broad range to both waveguides. In the experiment described in [17] we used two sections of a rectangular waveguide with the cut-off frequency 0.9 GHz. Our waveguide was multi-modal above 2 GHz, and in the range 1-2 GHz supported an only  $TE_{10}$  mode. In work [17] two waveguide section were separated by a gap whose length L did not exceed the the waveguide width D. One of these sections was excited by a built-in antenna with a broadband matching circuit and a similar antenna received the signal in the other section. In presence of the wire-medium slab inserted between two waveguide sections the transmission coefficient  $S_{12}$  between two waveguide ports increased drastically and when the penetration depth d of the wires into the waveguides was small (of the order of the wire-medium period a)  $S_{21}$  turned to be quite uniform versus frequency in the range 1-2 GHz. Simultaneously, the reflectance  $S_{21}$  (fully associated with the reflection from the interfaces of the wire-medium slab) was below -10 dB.

In [17] the wire-medium slab guided a wave package of the modes of an unbounded wire medium. All these modes are practically TEM-waves propagating with the same phase and group velocities nearly equal to the speed of light in free space. These modes differ from one another only by the transverse component of the wave vector [14]. For a finite-width wire-medium

sample the spatial spectrum of these modes is determined by the width (more details can be found in [18]). No unusual modes of WMEs were revealed in [17] since the length  $L + 2d \approx L$ of the wire-medium sample was smaller than its maximal transversal size D. In the present paper we reveal them due to the drastic increase of L keeping all other components of the structure the same as in [17]. The same waveguide sections are used in our microwave experimental model and simulations. Similarly to [17] we excite our WME by the  $TE_{10}$  mode of the transmitting waveguide section of sizes  $82 \times 164$  mm, where two 1 mm gaps prevent the electric contact of the wires with the waveguide walls. The transmitting section is fed by a wave port and a similar port is assumed to be in the receiving section. We simulated the S-parameters, the electric and magnetic field distributions, and the Poynting vector distributions in the frequency range [1, 2]GHz for the case when the WME is absent and for the case when the WME is present. In the first case,  $S_{11} \neq 0$  arises due to the reflection of the waveguide mode from the open end of the transmitting waveguide. It is a very significant reflection ( $S_{11} \approx -2 \cdots -4$  dB at 1 - 2 GHz). In the second case,  $S_{11}$  arises due to the imperfect conversion of the waveguide mode into the modes of the WME and vice versa. This reflectance is low ( $S_{11} < -10$  dB) for all simulated structures - with the straight and bent endoscopes.

## 3.1. Straight endoscope



Fig. 4. Transmission  $S_{21}$  and reflection  $S_{11}$  coefficients versus frequency for the straight WME connecting two rectangular waveguides and excited by a distributed wave port. Top inset shows the simulated structure. Three typical frequencies  $f_{1-3}$  are marked on the plot of  $S_{11}$ .

We start from the study of a straight WME shown in the top inset of Fig. 4. The plot of this figure presents both reflectance and transmittance versus frequency in presence of the WME. In absence of the WME  $S_{11}$  varies within the interval [-2, -4] dB and  $S_{21}$  is below -10 dB. In presence of the WME S-parameters change drastically. The reflectance drops to the values below -12 dB at all frequencies. A so good operation of the transition layer is granted by the insertion depth d = a close to the optimum (though a rather efficient transition layer is formed for all d satisfying to the condition  $0 < d \ll \lambda$ ). However,  $S_{11}$  experiences maxima and minima repeating versus frequency .

The reflection maxima are smooth and located over the frequency axis not periodically. The minima of the reflectance are sharp, deep and also not periodic versus frequency. Therefore, the

dispersion of the reflectance cannot be identified with the set of Fabry-Perot resonances.

Aperiodic frequency oscillations, though not so strong, are also inherent to  $S_{21}$ . Minima of  $S_{21}$  in Fig. 4 are not as deep as they were in the previous subsection. However, they are sharp and become deeper versus frequency. Analyzing their growth rate it is easy to extrapolate these minima of  $S_{21}$  from the optical lengths kL < 30 corresponding to the present case to the optical lengths kL > 200 corresponding to our THz endoscope. This extrapolation gives us the similar depth of the transmittance minima  $S_{21} = -20 \cdots - 25$  dB as we have seen in Figs. 2(a) and 3(b). This brings the understanding that the sharp minima of the transmittance we obtained for our THz endoscope are related to radiative losses and do not depend on the conductivity of the wires or properties of the porous matrix. We approach to the understanding that the characteristics of our THz endoscope are mainly determined by the unusual eigenmodes of elongated wire medium samples.



Fig. 5. Straight WME at frequency  $f_1$ : (a) – Color map of the electric field amplitude in the central longitudinal cross section. (b) – Color map of the Poynting vector distribution in the same cross section.

Next, we select in the plot Fig. 4 three typical normalized frequencies  $(f_1, f_2 \text{ and } f_3)$  and depict for these frequencies the spatial distributions of the electric field amplitude and Poynting vector. Frequency  $f_1 = 1.475$  GHz is that of a sharp local minimum in the reflectance and corresponds to a smooth local maximum of  $S_{21}$ . Frequency  $f_2 = 1.500$  is that of a local maximum of reflectance and corresponds to a sharp local minimum of  $S_{21}$ . Frequency  $f_3 = 1.506$  GHz corresponds to neither maximum nor minimum of  $S_{21}$  (though corresponds to the minimum of  $S_{11}$ ). In Fig. 5, corresponding to  $f_1$ , we see the field and power flux color maps typical for a usual wire-medium slab. The field distribution has no sharp maxima and minima and the distribution of the Poynting vector shows no local reflection and vortices. Radiation losses though arise at the edges of the waveguide sections are very weak. At this frequency our WME guides a package of the modes of an unbounded wire medium [17, 18]. It is excited in the first transition layer, propagates along the WME towards the second one, and transforms there back into the TE<sub>10</sub> (waveguide) mode.

A very different wave process is depicted in Fig. 6, corresponding to frequency  $f_2$ . The distribution of the field over the endoscope cross section becomes spatially oscillating and subwavelength transversal concentration of the electric energy arises. In a narrow axial domain of the WME the power travels forward, and in the peripheral domain it travels backward. We have checked that the similar vortex of power is inherent to all sharp minima of  $S_{21}$ . At these frequencies the radiation loss factor  $P = 1 - S_{11}^2 - S_{21}^2$  experiences the local maxima and



Fig. 6. The same as in Fig. 5 but at frequency  $f_2$ .



Fig. 7. The same as in Figs. 5 and 6 but at frequency  $f_3$ .

corresponds to a rather strong radiation from the ends of the waveguide sections. This radiation is visually detectable in Fig. 6(b). As to frequency  $f_3$ , two color maps depicted in Fig. 7 allow us to guess a superposition of a wave package of the usual TEM-polarized modes of an infinite wire medium and the vortex modes.

When the waveguide is straight the vortex modes are seen in the color maps of the Poynting vector only at frequencies of the local minima of  $S_{21}$  and at frequencies very close to these minima. At some of these frequencies the backward flux is seen in the peripheral (as in Fig. 6) part of the endoscope. At other frequencies the backward flux is seen in the axial part of the WME. At frequencies sufficiently distant from the local minima the presence of the vortex mode manifests in the color maps only in the subwavelength non-uniformity of the flux distribution across the WME and in the visible radiation from the endoscope faces. The noticeable decrease of the forward Poynting vector occurs either in the peripheral or in the axial parts of the WME. For example, at frequency  $f_3$  the vortex mode corresponds to the axial backward flux, though the forward flux associated with the usual wire-medium mode still overweights in the axial domain.

We have done a similar analysis for many other frequencies, and for the straight WME having the tilted faces (wires of non-equivalent length) varying the tilt angle  $\alpha$  from zero to 60°. All these modifications of the endoscope do not matter for our general observations because we always observed the similar frequency dispersion of the *S*-parameters as that in Fig. 4 and the similar distributions of the field and power flux at the characteristic frequencies. The first general observation is that the vortex modes in a sample of parallel wires arise if  $L \gg D$  i.e. if the wire-medium slab is an endoscope. The second observation is that the frequencies at which the vortex modes result in the minimal transmittance (maximal radiation loss) alternate with the frequencies at which the vortex modes are practically absent and radiation losses are negligibly small. The third observation is the quasi-TEM polarization of the vortex modes. Notice that for better understanding of these properties we have created and watched dozens of CST Studio Suite animation movies.

Thus, an extensive numerical study of the straight WME allows us to formulate the following conclusions:

- Unusual modes with the power vortices and quasi-TEM polarization are inherent to any WME and result in the sharp minima of the transmittance/maxima of the radiative loss and reflectance over the frequency axis;
- Radiation related to the vortex modes arise on the faces of the WME which is strongly mismatched at the corresponding frequencies;
- At the maxima of the transmittance the vortex modes are weakly excited, the radiative losses are practically absent, and the WME operates like a usual wire-medium slab.

## 3.2. Bent endoscopes

To understand how the bending may change these conclusions we have performed extensive studies of the bent WME. In these studies the effective radius R of the curvature is changed in accordance to the bending angle  $\theta$  i.e. the bending is uniform and the endoscope axis represents an arc of a circle. In one set of numerical simulations we bent the endoscope keeping the same length L of its wires as in the previous subsection. The equivalence of all wires length L for a bent WME implies the tilt of either one face or both faces of the WME with respect to the endoscope axis. When one face is tilted, as in Fig. 8, its tilt angle  $\alpha$  shown in Fig. 8(b) is twice larger compared to the case when both faces of the endoscope are equally tilted. We have studied both these cases for the WME of equivalent wires. In another set of simulations we have studied the structure when the tilt of the faces is absent for  $\theta = 90^{\circ}$  and present for other bending angles. In this case the lengths of the wires are different and lie in the interval  $[L - D\pi^2/4, L + D\pi^2/4]$ . We have unbent this endoscope and performed the same simulations for two cases: when an only face is tilted and when both faces are equally tilted. Finally, we have studied the structure when the tilt of the endoscope faces is absent for  $\theta = 180^{\circ}$  and present for other angles. We simulated this WME in the cases  $\theta = 90^{\circ}$  and  $\theta = 0$  when both faces are tilted. In all these cases the conclusions formulated for the straight WME kept valid. The tilt of the interface, the slight non-equivalence of the length of wires, even the radius of the endoscope curvature decreased to the values of the order of  $\lambda$  – all these factors turned out to be insignificant. The operation of the bent endoscope is qualitatively not different from the operation of the straight one.

All frequency dependencies of  $S_{11}$  and  $S_{21}$  obtained for  $\theta = 90^{\circ}$  and  $\theta = 180^{\circ}$  in all cases (equivalent wires, non-equivalent wires, normal faces, tilted faces) turned out to be qualitatively similar to those of Fig. 4. The only difference is slightly lower values of the maxima of the transmittance and different frequencies of the maxima and minima. These frequencies depend on  $\theta$  and for the given  $\theta$  are different for endoscopes with two tilted faces, one tilted face and two non-tilted faces.



Fig. 8. WME with bending angle  $\theta = 90^{\circ}$  at frequency of type  $f_1$ : (a) – Color map of the Poynting vector and (b) – color map of **E**.

Also, the color maps of the electric field and Poynting vector for the bent endoscope are noticeably different from those of the straight one. Figures 8-10 correspond to a WME with the bending angle  $\theta = 90^{\circ}$  having the same length of all wires that corresponds to the tilt angle  $\alpha \approx 50^{\circ}$  of the output face. These three figures correspond to three typical frequencies chosen in accordance to the same principle as above. In the present case  $f_1 = 1.20$  GHz corresponds to a local maximum of  $S_{21}$ ,  $f_2 = 1.62$  GHz corresponds to a local minimum, and  $f_3 = 1.48$  GHz is in the middle between a local minimum and a local maximum of the transmittance.



Fig. 9. The same as in Fig. 8 but at frequency of type  $f_2$ .

Color maps in Fig. 8 are not very different from those calculated for the straight endoscope. Vortex modes can be guessed in this picture, perhaps, only through a noticeable non-uniformity of the guided mode field and power flux across the WME. Also, they can be guessed via the power flux directed to free space from the faces of the WME. So, unlike the straight endoscope, in the bent one the vortex modes are induced even at the maxima of the transmittance.

In Fig. 9 we see a clear qualitative difference of the vortex mode in a bent WME from that excited in a straight WME. Namely, the endoscope curvature results in the localization of the power vortices along the axis. We may see the areas in which the power flux changes the sign. Here, the vortex modes imply a more non-uniform distribution of the electric field. We may speak on the *strongly* subwavelength field concentration. However, similarly to the observed for a straight WME at frequency  $f_2$ , the backward power flux is noticeably lower than the forward one.



Fig. 10. The same as in Figs. 8 and 9 but at frequency of type  $f_3$ .



Fig. 11. WME with bending angle  $\theta = 180^{\circ}$  at the corresponding frequency  $f_2$ . Color maps of the Poynting vector (a) and the electric field (b).

Figure 10 corresponds to frequency  $f_3$ . Here we also observe the local vortices that we could not see for the straight WME at such frequencies. At frequency  $f_3$  the backward flux related to these vortices is much smaller than the forward one. However, in general the vortex modes in the bent WME are more pronounced than in the straight one. This results in some frequency-averaged bending losses.

The study of more curved endoscopes e.g. that with  $\theta = 180^{\circ}$  has shown a peculiarity of a so severely bent endoscope. If only one of two faces is tilted so that to preserve the equivalent L of all wires, this face turns out to be strongly mismatched with the waveguide. Then the frequency dispersion of S-parameters manifests the Fabry-Perot resonances masking the effect of the vortex modes. This turns out to be so because in this case some wires of the array are embedded too deeply into the waveguide – d becomes comparable with  $\lambda$  and the transition layer is not formed on the tilted endoscope face. If both faces of this WME are equally tilted these faces keep sufficiently matched with the waveguide and the WME operates like a straight one and like that with the bending angle  $\theta = 90^{\circ}$ . In Fig. 11 we depict the color maps for  $\theta = 180^{\circ}$  at its frequency of type  $f_2$ . Local vortices clearly dominate at this frequency. The leakage of radiation into free space still occurs from the faces of the WME.

We performed the analysis of the loss factor P that allowed us to make a general conclusion: bending the endoscope in different ways (keeping the same lengths of all wires by price of the tilted endoscope faces or stretching the wires so that the faces keep normal to the axis) slightly increases the frequency-averaged radiative loss. However, the main action of the bending is the shift of the frequencies of the transmittance local minima. Notice, that in [12] two deep local



Fig. 12. Power loss versus normalized frequency for three cases: straight WME, that with  $\theta = 90^{\circ}$  and that with  $\theta = 180^{\circ}$ . Simulations.

minima of transmittance were fixed and they also were shifted along the frequency axis due for the bending. However, since in [12] Fabry-Perot resonances were not suppressed the physics of these minima was not clarified. Since the endoscope was very short the shift of these minima for a bent WME was quite small, and the transmittance at the MRI operation frequency changed slightly. For an optically long WME the bending drastically changes both  $S_{21}$  and P at a given frequency.

In Fig. 12 we depict P(f) for three angles of bending for the case when the endoscope has the unique length *L* of all wires. For  $\theta = 0$  the frequency-averaged loss factor  $\langle P \rangle$  equals to 0.19. The frequency maxima of P(f) correspond to the minima of  $S_{21}$  that clearly relates this mismatch to the vortex modes. For  $\theta = 90^{\circ}$  the frequency-averaged loss factor is equal  $\langle P \rangle \approx 0.27$  and for  $\theta = 180^{\circ}$  we have  $\langle P \rangle \approx 0.45$ . At a first glance, the traditional concept of the bending losses keeps valid. However, it is not so, because the traditional concept implies  $R \gg \lambda$  because any conventional endoscope cannot operate if  $R < \lambda$  [2]. For our WME the case  $\theta = 90^{\circ}$  corresponds to  $R \approx 2\lambda$  at 1.5 GHz, whereas  $\theta = 180^{\circ}$  implies  $R < \lambda$  at f < 1.5 GHz. A so modest growth of the frequency-averaged loss accompanying a so severe bending means that the traditional concept of bending losses factor is rather high even for a straight endoscope. This was noticed in [12]. Now we understand that it is an implication of the vortex modes resulting in the radiation from the endoscope faces.

## 4. Microwave experiment



Fig. 13. Pictures of our microwave model experiment: (a) – Straight WME, (b) –  $\theta = 90^{\circ}$ .

In order to validate these conclusions experimentally we have built several samples of a model WME. The geometry of the WME is the same as in our simulations. The main difference in the WME is nonzero losses in the metal. However, on the background of high radiative losses inherent to a WME, dissipative losses are not important. Instead of an abstract wave port used in simulations, our waveguide sections are terminated by built-in dipole antennas with an adaptive broadband matching circuit. Such the antenna system could not be adequately simulated in the previous section.

Two of our samples are pictured in Figs. 13(a) and 13(b). They correspond to the straight WME ( $\theta = 0$ ) and to that with the bending angle  $\theta = 90^{\circ}$ . In these sample with  $\theta = 180^{\circ}$  the face tilt angle  $\alpha$  is zero. In the other bent endoscopes as well as in the straight one  $\alpha$  is kept nonzero so that to keep the same lengths of all wires as in the endoscope with  $\theta = 180^{\circ}$ . We have also manufactured and studied the similar WMEs with nonzero  $\alpha$  and bending angles  $\theta = 115^{\circ}$  and  $\theta = 210^{\circ}$ . These additional studies did not change our conclusions.



Fig. 14. Measured S-parameters of our microwave WME versus frequency for three bending angles from zero to  $\pi$ : (a) – transmittance and (b) – reflectance.

In Fig. 14(a) we depict the frequency dispersion of the structure transmittance for the straight endoscope and for two its bent analogues – that with  $\theta = 90^{\circ}$  and that with  $\theta = 180^{\circ}$ . For the WME with  $\theta = 90^{\circ}$  the frequency-averaged transmittance is lower due to deeper local minima. However, this decrease has nothing to do with the bending losses. Really, for  $\theta = 180^{\circ}$  the frequency-averaged value of  $S_{21}$  is higher than for  $\theta = 90^{\circ}$  though the radius of the endoscope

curvature is twice as smaller than that one for  $\theta = 90^{\circ}$ . Namely, for  $\theta = 180^{\circ} R = \lambda$  at frequency 1.5 GHz, and below this frequency it is a subwavelenth value.

In Fig. 14(a) we show the frequency dispersion of the structure reflectance and can see that the minima of the transmittance correspond to the maxima of the reflectance. From two plots presented in Fig. 14 it is possible to calculate the power loss  $P = 1 - S_{21}^2 - S_{11}^2$  that can be practically identified with radiation loss. In the maxima of transmittance this value does not exceed 0.2 - 0.3, but at the local minima of transmittance P attains 0.7 - 0.8. This result completely fits our previous numerical studies and allows us to associate the local minima of  $S_{21}$  with the vortex modes.



Fig. 15. S-parameters of the structure for the case  $\theta = 115^{\circ}$  with and without the WME: (a) – transmittance and (b) – reflectance.

One more confirmation of our numerical model results is granted by the comparison of  $S_{21}$  and  $S_{11}$  with the corresponding S-parameters of the waveguide structure in absence of the WME. This comparison is presented in Fig. 15 for the case  $\theta = 115^{\circ}$  (to stress that the value of  $\theta$  does not matter for this qualitative analysis). In absence of the WME two waveguide sections forming the angle  $\theta$  are weakly coupled via side-lobes the open end pattern. Since this pattern is frequency-dependent the transmittance is strongly dispersive, however, basically it is approximately -30 dB in the whole frequency range. The reflectance  $S_{11}$  in the circuit of the transmitting antenna within the frequency interval [1.1, 1.9] GHz is below -20 dB, i.e. the power is almost completely radiated into free space. Introducing the bent WME between the waveguide sections we increase

the transmittance from one waveguide section to the other one by 15 - 25 dB. Simultaneously, the dispersion of the reflectance in Fig. 15(b) acquires the sharp minima and smooth maxima.



Fig. 16. Power loss versus frequency for three cases: straight WME, that with  $\theta = 90^{\circ}$  and that with  $\theta = 180^{\circ}$ . Experiment.

We have calculated the power loss factor P(f) from the measured S-parameters. We cannot directly compare P presented in Fig. 16 with that depicted in Fig. 12 because the simulation model differs from the experimental setup. However, qualitatively P(f) in Fig. 12 and P(f) in Fig. 16 are similar in their main features – maxima of P correspond to frequencies at which the vortex modes dominate and the impact of the severe bending to the frequency-averaged loss factor is not drastic. In our experiment  $\langle P \rangle = 0.38$  for  $\theta = 0^{\circ}$ ,  $\langle P \rangle = 0.40$  for  $\theta = 90^{\circ}$ , and  $\langle P \rangle = 0.41$  for  $\theta = 180^{\circ}$ . These values qualitatively agree with what we have obtained in our model simulations.

In general, all our experimental data show that the frequency dispersion of the measured S-parameters and the radiation loss factor P of the microwave WME (both straight and bent ones) qualitatively agree with those obtained in our numerical simulations. Bending the WME we slightly increase the frequency-averaged radiative losses but noticeably modify the frequency dispersion of the transmittance/reflectance/power loss factor. So, our microwave experiment confirms that in the WME there are vortex modes competing with the modes of an infinite wire medium. Frequencies at which the vortex modes dominate depend on the bending radius R and the face tilt angle  $\alpha$ .

# 5. Discussion and conclusions

This paper was initially targeted to the study of the bending losses for a wire-medium THz endoscope. However, the conventional concept of the bending losses for such endoscopes turned out to be irrelevant. For an optically short WME this was already noticed in [12], now we may claim it for a long WME. The WME severely bent so that  $R = (0.5 - 2) \cdot \lambda$  operates basically similarly to the straight endoscope: frequency-averaged losses slightly increase but this increase is not critical. Losses in a WME are mainly radiative and arise due to the power vortex inherent to the eigenmodes of such endoscopes. The radiation related to these modes arise on the ends (faces) of the WME whereas the radiation from the curved endoscope itself is practically absent.

The most critical for a WME is the strong impact of the bending to the frequency dispersion of the endoscope. This dispersion comprise sharp minima of transmittance (maxima of radiative power loss). The displacement of these minima along with the bending for a long WME is much larger than the slight shift noticed for a short WME in [12]. It makes the practical application of a THz WMEs operating in a narrow frequency band very difficult. Even a slight bending may

transform the frequency of the transmission maximum/loss minimum into the frequency of the transmission minimum/loss maximum.

However, the present paper is only our first step towards the sufficient understanding of WMEs. We have not yet studied the influence of the array geometry to the dispersion of the straight and bent endoscope. There is no hope to avoid the vortex modes because we detect them even for a very short WME of [12]. However, we hope that one may design a WME for which the vortex modes would be robust to the bending.

If a WME is targeted to the ultra-broadband operation, its bending does not drastically damage its transmissive properties. In work [19] the possibility of the non-resonant THz imaging by a wire-medium slab impinged by ultra-broadband (single-cycle) pulse is proved. In this paper  $D \ll L$  and the wire-medium slab is not a WME. Is it possible for a WME? In a WME the vortex modes make the frequency-averaged radiative loss factor < P > rather high even for a straight endoscope. In our microwave study we obtained < P > ~ 0.3 - 0.5. This power loss would be acceptable for an endoscope with ultra-broadband operation. However, the optical length of a practical endoscope is larger by an order of magnitude than that in our microwave study. We still do not know how < P > depends on the optical length for a very long endoscope. It seems that these losses are not directly related to the endoscope length. However, this issue needs to be specially studied.

In our next paper we aim to find the answers for two questions: how to make the frequencies of the vortex modes robust to the bending, and how the frequency-averaged radiative loss factor of the WME depends on the wire array dimensions.

# Funding

Finnish Government Scholarship Pool of the Center for International Mobility CIMO (KM-16-10012); Ministry of Education and Science of the Russian Federation (ZadanieNo. 3.2465.2017/4.6).