Terahertz and Infrared Spectroscopy of Bacterial Nanofilaments

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***Abstract* — By means of terahertz and infrared (THz, IR) spectroscopies we have measured the dielectric response of nano-filaments of electrogenic bacteria *Shewanella oneidensis* MR-1 in a wide frequency and temperature ranges. THz-far-IR spectra are dominated by absorption due to bound water. At helium temperatures and at sub-THz frequencies a boson-peak-like excitation is detected that is typical for disordered materials. The observation is in agreement with the heat capacity measurements.**

I. INTRODUCTION

Various bacterial filaments represent the class of extremely interesting highly organized biological objects. They exhibit significant anisotropy having 3-12 nm width and 1-10 micrometers length. Some of them are associated with long-range electron transport phenomena, like *Geobacter sulfurreducens* [1] and *Shewanella oneidensis* MR-1 [2] (see Fig. 1) and other electrogenic bacteria. *S.oneidensis* MR-1 are able to reduce different oxidants by electronic transfer via extracellular appendages, which are supposed to be a part of periplasmic membrane [3] filled with complexes of multiheme conductive cytochromes [4].

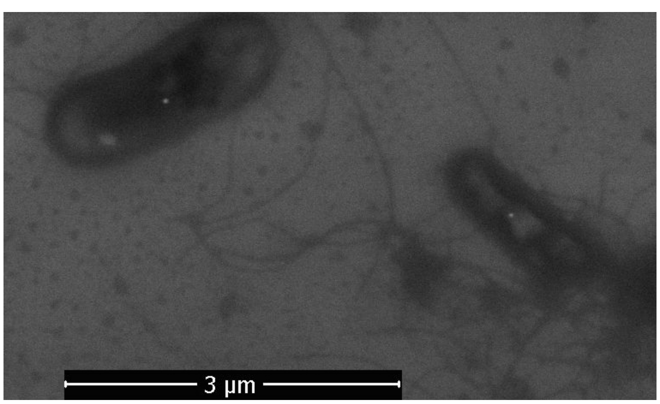

Fig.1. Electron microscopy image of *Shewanella oneidensis* MR-1 with conductive filaments around.

II. METHODS

With a set of spectrometers, spectra of complex dielectric function of conductive filaments of electrogenic bacteria *Shewanella oneidensis MR-1* were measured in the terahertz-infrared spectral range, at frequencies from 0.1 to 200 THz and at several temperatures from 300 K down to 5 K. The reference experiments were performed on lyophilized powder of bovine cytochrome c and bovine serum albumin. In addition to spectroscopic studies, measurements of pili and cytochrome c heat capacity were carried out in the temperature range 2 - 300 K.

III. RESULTS

At room temperature, the THz-far-IR spectra are dominated by vibrational response of bound water molecules and clusters located within/between filaments, see Fig.2. Below 10 cm^{-1} a well known Debye H_2O-relaxation peak is seen (cyan). Two bands observed at 200 cm^{-1} (magenta) and 600 cm^{-1} (blue) are assigned to translational and librational vibrations of bound water molecules, respectively. The origin of 50 cm^{-1} peak (yellow) remains unresolved. A set of narrow resonances observed above 1000 cm^{-1} corresponds to intramolecular vibrations of protein molecules. The intensities of the water-related IR-resonances decrease at low temperatures and remain observable down to the lowest temperatures, while the Debye contribution freezes out below 200 - 250 K. The temperature dependences of the THz permittivity/conductivity spectra and of the heat capacity demonstrate the presence of

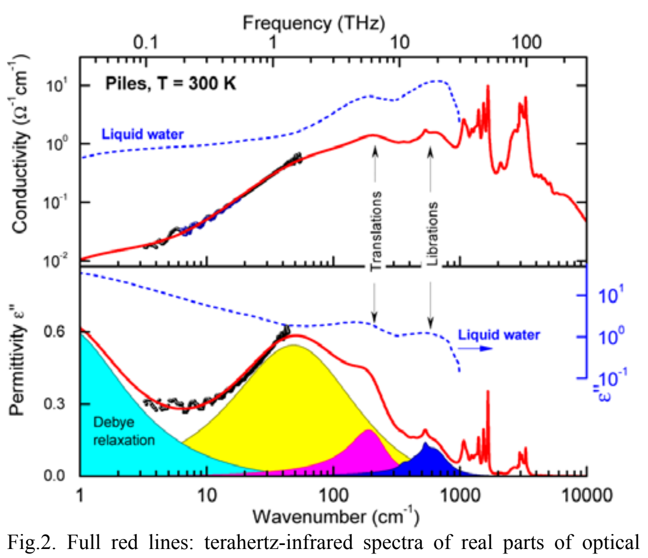

Fig.2. Full red lines: terahertz-infrared spectra of real parts of optical conductivity (upper panel) and of dielectric permittivity (lower panel) of bacterial filaments obtained at 300 K by fitting the spectra of transmission and reflection coefficients of the samples. Dashed lines show spectra of liquid water taken from [5]. Arrows indicate translational and vibrational H_2O modes. Separate contributions to the spectra are shown with colors (see text).

“liquid-water — ice” phase transition which takes place at 250 K. This cryoscopic effect clearly points out that the water in the studied objects persists in an associated form. At liquid helium temperatures, we detect a weak signature of a resonance absorption around 0.5 THz. Our analysis of the temperature evolution of the resonance and of the heat capacity of the sample allows us to associate the origin of the absorption with a boson peak phenomena [6], i.e. with the manifestation of an extra (with respect to the Debye contribution) acoustic phonon states arising in disordered media. The behavior of heat capacity (see Fig. 3) at sub-helium temperatures (below 2 K) testifies the presence of glassy phase. Additional low temperature feature in pili and cytochrome c heat capacitance has currently unknown nature.

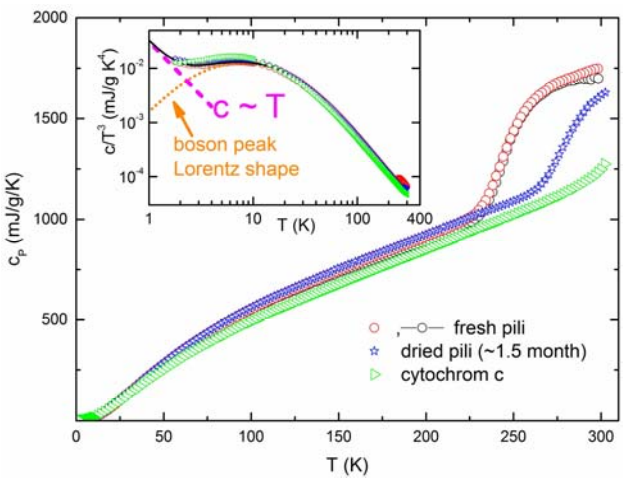

Fig.3. Temperature dependence of heat capacity of freshly prepared filaments (red and black circles), dried pili (blue stars) and amorphous cytochrome c (green triangles). In the inset the same data is plotted in the C_p/T^3 – T coordinates.

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