Quasi-Optical Resonant Single-Frequency Flaw Detector of Polymer Filament for 3D Printing

D D Teterina, I O Dorofeev and A V Badin
Faculty of Radiophysics, Tomsk State University, 36, Lenina av., Tomsk, 634050, Russia
teterinadar@gmail.com

Abstract. In the paper quasi-optical resonant single-frequency flaw detector for investigation of heterogeneity of 3D printer polymer filament are described. A scheme of quasi-optical flaw detector based on 10 GHz open resonator with a filament broaching mechanism is given. Industrial filaments based on polystyrene, polyethylene terephthalate glycol and acrylonitrile styrene acrylate were tested in a flaw detector. The measured amplitudes at the maximum of the resonance curve in the presence of a filament in the inside of the resonator are presented.

1. Introduction
Additive printing technologies are currently widely used in the creation of various objects. As for the applications of 3D printing in electronic equipment [1-4], in addition to the mechanical properties of such objects, the electrophysical properties of the material used also play an important role. In this case, a joint solution of the problems is possible, both of creating load-bearing structures, and of electromagnetic compatibility and protection from radio emission of individual units and devices.

This approach requires the creation of an initial filament for 3D printing with specified electrophysical parameters [8-14]. It is also required to ensure the constancy of these parameters during the printing process. The best option here is to use continuous non-destructive testing of fiber throughout its length. It is essential that the control should be radio wave and be carried out at frequencies close to the operating frequency of the device in which the material will be applied. Given the small transverse dimensions of the fiber compared to the wavelength in the microwave ranges, it is advisable to use resonator methods. Sensors based on open resonators possess a number of important advantages when creating resonant sensors, which ensure the free placement of a controlled fiber section in a resonant volume, a sparse frequency spectrum, and high quality factor of oscillations in a wide frequency range. The free placement of an object is important not only in terms of ease of access to it, but also in terms of the optimal selection of its position in order to minimize the effects of its vibrations and movements in the resonant volume on the output signal.

2. Problem definition
In the simplest case, the filament diagnostic device consists of a highly stable microwave generator, open resonator [15-18], microwave oscillation detector, processing and indication device. The principle of its operation is to fix the change in the signal at the resonator output, which is due to a change in the filament parameters. Such device can operate in the measurement mode of
parameter of the fiber, for example, the diameter with a constant value of the dielectric constant, or vice versa. In this case, calibration of the scale by reference samples is required. The second mode is fixing a small local (less than the diameter of the beam) heterogeneity of either diameter or permittivity. One of the main types of resonator oscillations is usually used, the deviation of the amplitude-frequency characteristic of which (the resonance curve) from the amplitude-frequency characteristic of the empty resonator is determined by the electrophysical characteristics of the introduced filament and their changes. Thus, the output signal level of a single-frequency converter is determined by tuning of the resonator and the properties of the portion of the fiber located in the resonant beam. To achieve maximum conversion steepness, various settings for fiber samples with different parameters are required.

3. Theory

3.1. Characteristics of a quasi-optical resonator with a polymer filament.

If the losses in the fiber are small, then the resonance curve of the resonator with the object relative to the empty cavity mainly undergoes a shift along the frequency axis (Figure 1a), since the diffraction loss at such an object is also small. In this case, it is advisable to tune the resonator so that the frequency of the generator is on the slope of the resonance curve of the resonator with the sample at about half power. This ensures maximum measurement of the output signal when the parameters of the stretched fiber deviate. The choice of a slope (low-frequency or high-frequency) is practically irrelevant here.

If the losses in the fiber lead to a noticeable broadening of the resonance curve relative to the resonance curve of the empty resonator, but its displacement along the frequency axis is small, it is advisable to combine the generator frequency with the peak of the resonance curve of the open resonator. The advantage here will be provided by a higher value of the signal itself.

Finally, if a change in the fiber parameters leads both to a shift of the resonance curve along the frequency axis and to its broadening (Figure 1c), then the point of optimal tuning may also be on the slope, but it is important to choose not only its position, but also the necessary slope (low-frequency, or high frequency).

3.2. System of quasi-optical resonant single-frequency flaw detector for heterogeneity of polymer filaments.

The device (Figure 2) contains a voltage-controlled oscillator (VCO) at a frequency of 10 GHz as a signal source, synchronized using a phase-locked loop in a reference highly stable crystal oscillator frequency (COF). To simplify the implementation of the circuit measuring the transmission coefficient of the measuring open resonator not only at the resonant frequency, but also at any given point in
the resonance curve, it is advisable to use a highly stable non-tunable generator, and to perform tuning by the resonator.

**Figure 2.** The experimental setup of quasi-optical resonant single-frequency flaw detector for heterogeneity of polymer filament for 3D printing.

The device has two detectors - for the reference signal excited directly by the generator, as well as the signal that passed through the resonator. Since the device is designed for a dynamic mode, in order to reduce the influence of displacements and vibrations of the filament when it is pulled, the conductor is inclined in the plane of the electric field in an open resonator. The signals from the detectors are recorded with a 12-bit analog-to-digital converter (ADC). The filament pulling mechanism is controlled by a 8-bit digital-to-analog converter (DAC) through a PC via the USB bus.

**Figure 3.** Appearance of the quasi-optical single-frequency flaw detector of heterogeneities of polymer filaments and a filament broaching system.

The open measuring resonator is placed in a protective shield (Figure 3), while the filament can be freely introduced and stretched through a sufficiently wide (about 1 cm) gap. The diameter of the mirrors of the open resonator was 160 mm; the radius of curvature was 200 mm.

4. **Approbation**

For the approbation of quasi-optical resonant single-frequency flaw detector 5 samples (Table 1) of industrial polymer filaments, polyethylene terephthalate glycol (PET-G), polystyrene (HIPS), acrylonitrile styrene acrylate (ASA), conductive acrylonitrile butadiene styrene, conductive
polylactide were selected. By the coaxial method at frequency of 10 GHz real (\(\varepsilon'\)) and imaginary (\(\varepsilon''\)) parts of the permittivity of printed test samples by additive technology were measured.

**Table 1.** Parameters of the filaments and signal level on detector 2 of quasi-optical resonant single-frequency flaw detector at maximum (\(V_{\text{def}}(P_{\text{max}})\)) of resonance curve.

| Sample                                      | \(D_{\text{filament}}\) (mm) | \(V_{\text{def}}(P_{\text{max}})\) (mV) | \(\varepsilon'\) (f=10 GHz) \(\text{(rel. units)}\) | \(\varepsilon''\) (f=10 GHz) \(\text{(rel. units)}\) |
|---------------------------------------------|-------------------------------|-----------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Empty resonator                             | 1309.4                        |                                         |                                                 |                                                 |
| Polyethylene terephthalate glycol           | 1.770                         | 1276.3                                  | 2.569                                           | 0.01866                                         |
| Polystyrene                                 | 1.765                         | 1267.2                                  | 2.253                                           | 0.00363                                         |
| Acrylonitrile styrene acrylate              | 1.713                         | 1256.9                                  | 2.429                                           | 0.02795                                         |

As follows from the table, the value of the transmission coefficient of the resonator at the resonant frequency is ambiguously associated with losses in the filament. This is possible in a certain region where, due to a decrease in losses in the volume of an object (ohmic or thermal losses) with a decrease in the tangential component of the electric field, provided that there are small diffraction losses of the resonant beam on the filament [19]. With the exception of this region, in other cases, the Q factor of the cavity decreases with increasing conductivity of the sample. Thus, as for an ultrathin conductor, for a polymeric fiber, it is also necessary to take into account the ambiguity, which consists in the fact that the same losses recorded by the resonator sensor can correspond to different fiber characteristics. This is especially true for a single-frequency sensor.

**Table 2.** Parameters of the conductive filaments and signal level on detector 2 of quasi-optical resonant single-frequency flaw detector at maximum (\(V_{\text{def}}(P_{\text{max}})\)) of resonance curve.

| Sample                                           | \(D_{\text{filament}}\) (mm) | \(V_{\text{def}}(P_{\text{max}})\) (mV) |
|--------------------------------------------------|-------------------------------|-----------------------------------------|
| Acrylonitrile butadiene styrene (conductive)      | 1.740                         | 282.8                                   |
| Polylactide (conductive)                         | 1.730                         | 5.8                                     |

As follows from table 2, an increase in the conductivity of the filament leads to a significant decrease in the quality factor of the resonator, which reduces the resolution of the sensor. Thus, the proposed method is most optimal for filaments with close values of the parameters (complex permittivity) and allows you to record small deviations in the characteristics of the filament. The deviation of the resonance curve from the initial value should not exceed half its width.

**Conclusion**

Thus, the possibility of using a quasi-optical resonator for flaw detection of heterogeneities of polymer composite for a 3D printer is shown. This system can be used in the production of filament for 3D-printers working on the fused deposition method, for the purpose of non-contact rapid analysis of the homogeneity of the manufactured product.

**References**

[1] Jaksic N I and Desai P D 2018 Characterization of resistors created by fused filament fabrication using electrically-conductive filament *Procedia Manuf.*, 17 37–44

[2] Kim K, Park J, Suh J hoon, Kim M, Jeong Y and Park I 2017 3D printing of multiaxial force sensors using carbon nanotube (CNT)/thermoplastic polyurethane (TPU) filaments *Sensors Actuators, A Phys.*, 263 493–500

[3] Flowers P F, Reyes C, Ye S, Kim M J and Wiley B J 2017 3D printing electronic components and circuits with conductive thermoplastic filament *Addit. Manuf.*, 18 156–63
[4] Chen Q, Chen X and Xu K 2017 3-D printed Fabry–Perot resonator antenna with paraboloid-shape superstrate for wide gain bandwidth Appl. Sci. 7 1134
[5] Kuleshov G E, Zhuravlyova Y V. and Dotsenko O A 2015 Electromagnetic response from composite radiomaterials based on multiwall carbon nanotubes at microwave frequencies 2015 Int. Sib. Conf. Control Commun. SIBCON 2015 - Proc. 0–4
[6] Kuleshov G E, Zhuravleva Y V. and Chernobrova D A 2014 Microwave electromagnetic parameters of composite radiomaterials based on carbon nanostructures and ferrimagnetics Int. Conf. Young Spec. Micro/Nanotechnologies Electron Devices, EDM 158–60
[7] Kuleshov G E and Badin A V 2019 Study of electromagnetic characteristics of polymer materials based on single-walled and multi-walled carbon nanotubes IOP Conf. Ser. Mater. Sci. Eng. 525 012030
[8] Bastola A K, Paudel M and Li L 2018 Development of hybrid magnetorheological elastomers by 3D printing Polymer (Guildf) 149 213–28
[9] Yang F, Zhang X, Guo Z, Ye S, Sui Y and Volinsky A A 2019 3D printing of NdFeB bonded magnets with SrFe$_{12}$O$_{19}$ addition J. Alloys Compd. 779 900–7
[10] Wang X, Jiang M, Zhou Z, Gou J and Hui D 2017 3D printing of polymer matrix composites: A review and prospective Compos. Part B Eng. 110 442–58
[11] Lei Z, Chen Z, Zhou Y, Liu Y, Xu J, Wang D, Shen Y, Feng W, Zhang Z and Chen H 2019 Novel electrically conductive composite filaments based on Ag/saturated polyester/polyvinyl butyral for 3D-printing circuits Compos. Sci. Technol. 180 44–50
[12] Fantino E, Chiappone A, Roppolo I, Manfredi D, Bongiovanni R, Pirri C F and Calignano F 2016 3D printing of conductive complex structures with in situ generation of silver nanoparticles Adv. Mater. 28 3712–7
[13] Sezer H K and Eren O 2019 FDM 3D printing of MWCNT re-inforced ABS nano-composite parts with enhanced mechanical and electrical properties J. Manuf. Process. 37 339–47
[14] Leigh S J, Bradley R J, Purssell C P, Billson D R and Hutchins D a. 2012 A simple, low-cost conductive composite material for 3D printing of electronic sensors PLoS One 7 1–6
[15] Dudorov S N and Lioubtchenko D V Open resonator technique for measuring dielectric properties of 3–5
[16] Badin A V, Bessonov V V, Dorozhkin K V, Dorofeev I O, Hiu L B and Dunaevskii G E 2018 Terahertz resonator diagnostics of filamentary dielectric objects proc. in 43th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz 2018) I-2
[17] Badin A V and Dunaevskii G E 2014 Optimization of resonator for local quasi-optical SHF and EHF diagnostics of inhomogenious materials anisotropy 2014 24th International Crimean Conference Microwave & Telecommunication Technology (Sevastopol: IEEE) pp 910–1
[18] Komiyama B, Kiyokawa M and Matsui T 1991 Open resonator for precision dielectric measurements in the 100 GHz band IEEE Trans. Microw. Theory Tech. 39 1792–6
[19] Dorofeev I O and Dunaevskii G E 2012 Losses in an open microwave resonator with an ultrathin cylinder 54 53–9