TEMPERATURE INSENSITIVE CURE CYCLE MONITORING OF CROSS-PLY COMPOSITE LAMINATES USING THE POLARIZATION DEPENDENT LOSS PROPERTY OF FBG

Geert Luyckx[1*], Damien Kinet[2], Nicolas Lammens[1], Karima Chah[2], Christophe Caucheteur[2], Patrice Mégret[2], Joris Degrieck[1]

[1] Materials Science and Engineering Department, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium

[2] Service d'Electromagnétisme et de Télécommunications, Faculté Polytechnique, Université de Mons, Boulevard Dolez 31, 7000 Mons, Belgium

**Geert.Luyckx@UGent.be*

Keywords: : Fibre Bragg grating sensors, Polarization dependent loss, cure cycle monitoring, residual strain monitoring.

ABSTRACT

A very important aspect of the composite manufacturing process is the appearance of residual strains and stresses during the curing cycle. Composites exhibit large residual strains after curing. Therefore, in this paper, we propose to follow the evolution of the polarization depend loss peaks (amplitude and wavelength) of fibre Bragg gratings during the manufacturing of the composite material to highlight the residual strains appearance.

1. Introduction

In general, structural health monitoring (SHM) of composite structures is considered very valuable certainly in terms of determining a correct maintenance or repair services. SHM, however, can already start at the beginning of the production process! A very important aspect of the composite manufacturing process is the appearance of residual strains and stresses during the curing cycle. Composites exhibit large residual strains after curing, which vary depending on the type of composite constituents, composite lay-up and manufacturing technology. The formation of thermal residual strains in unidirectional and cross-ply laminates arises mainly from the difference in thermal expansion between the reinforcement fibres (~ -0.55×10^{-6}) and the matrix (or resin) material (~30×10^{-6}). The highest residual strains are to be expected in the through-the-thickness direction (transverse).

In this paper, we explore the possibility of using the polarization dependent loss (PDL) of uniform fibre Bragg gratings (FBGs) to measure occurring residual strains in a carbon/epoxy plate. As will be explained, this type of measurements have some advantages over the conventional methods. Further on, an estimation of the transversally occurring residual strain is given.

2. Optical fibre sensing

2.1. Fibre Bragg grating sensors: general principle

Optical fibre sensors are ideal candidates as monitoring systems in composite structures. The sensing capabilities of optical fibres Bragg gratings (FBGs) come from sending light through the optical fibre and studying how it interacts with a so-called grating written in the core of the fibre. This grating is a localized periodic modification (pitch Λ) of the refractive index (n) of an optical fibre (Figure 1). When launching a broadband light signal in the optical fibre, part of the spectrum gets reflected at the Bragg grating, with the central wavelength of the reflection determined by the Bragg-wavelength:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

When the optical fibre is strained, the grating pitch and the refractive index (the strain-optic effect) will change, and so will the reflected wavelength, resulting in a sensor for axial strains (and transverse strains via the Poisson effect). The strain-optic effect is sensitive to all strain field components, including transverse strain. A change in transverse strain field will create two orthogonal polarization directions within the optical fibre, each with a different refractive index. Coupling light into such an optical fibre, will force the light to follow one of both orthogonal polarization directions. Depending on the polarization of the light, a different refractive index will exist, leading to a total of two (one for each polarization direction) different reflected wavelengths in a FBG (also called birefringence). Similar effects are seen when the FBG is exposed to changing temperatures. Thermal expansion and the thermo-optic effect will cause a shift of the Bragg wavelength. All these sensitivities can be summarized in formulas as in [1] (assuming a centre-strain approximation):

$$\Delta\lambda_{B,1}/\lambda_{B,1} = \varepsilon_3 - n^2/2\,(p_{11}\varepsilon_1 + p_{12}[\varepsilon_2 + \varepsilon_3]) + \beta\Delta T \tag{2}$$

$$\Delta\lambda_{B,2}/\lambda_{B,2} = \varepsilon_3 - n^2/2\,(p_{11}\varepsilon_2 + p_{12}[\varepsilon_1 + \varepsilon_3]) + \beta\Delta T \tag{3}$$

The parameters p_{11} and p_{12} are called the 'strain-optic coefficients' and are determined by the composition of the silica used in the fibre, the strain ε_3 is directed along the axis of the optical fiber, while ε_1 and ε_2 are transverse strains.

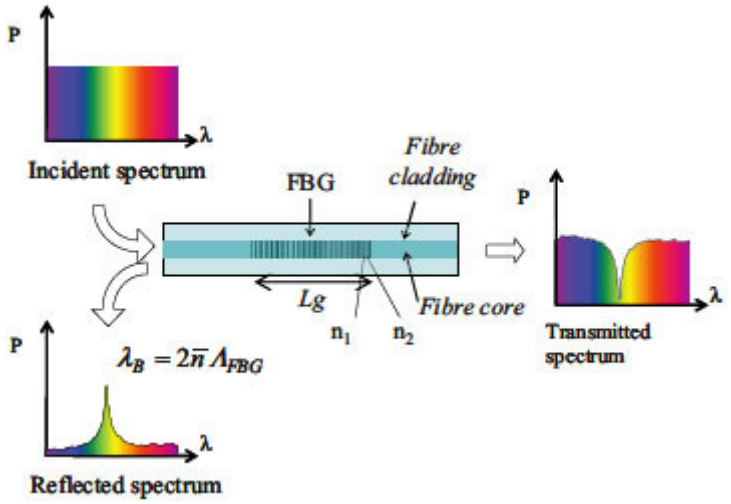

Figure 1: Principal of optical fibre Bragg grating [2]

As can be seen from (2) – (3), a difference in both transverse strains will lead to a birefringence at the position of the FBG. The equations (2)-(3) determines the shift of the

central wavelength of each reflected peak. Due to the finite bandwidth of these peaks however, at small separations of the central wavelength, the flanks of both peaks still overlap. In normal interrogation equipment, the detector is (intentionally) insensitive to polarization, and only detects the total amount of light. Fully accurate peak detection can only start when the peaks are fully separated. Such a level of peak separation will not occur in normal cure cycles, and usually even the first hints of peak separation will only start showing at the end of the cooling cycle (Section 3). The results from a normal FBG interrogation system will therefore be insufficient for accurately transverse residual strain monitoring when using conventional Bragg gratings.

One possible solution to this problem is the use of polarization maintaining (PM) fibre. In such fibres two polarization axes are deliberately created during their production of the fibre with a difference in the refractive index along both axes – these fibres are also known as high-birefringence of HiBi. In the case of an FBG, this leads to full peak separation of the Bragg spectrum even in the absence of external loads. While these fibres are capable of sensing transverse strains earlier during the curing cycle, they have significant downsides. Any type of PM fibre will require the knowledge of the exact embedding orientation, in order to interpret the results [3]. This requires careful manual placement of the fibres during production cycle (not industrially feasible) or specialized equipment, which can detect the fibre orientation after curing (expensive and impractical for larger structures).

2.2. Polarization Dependent Loss as measurement principle

The PDL of a device-under-test (DUT) is the ratio of maximum transmitted power to minimum transmitted power with respect to all possible states of polarization at a given wavelength, expressed in dB. The details of how PDL is measured will not be discussed in this work therefore the reader is referred to [4], this work will only briefly explain what PDL is, and how it can be used to perform strain measurements. When an optical fibre is used as DUT, the PDL is expressed as:

$$\mathrm{PDL}(\lambda) = \left|10\log_{10}\left(T_x(\lambda)/T_y(\lambda)\right)\right| \tag{4}$$

Where $T_{x/y}$ represents the transmitted power along the x (y) polarization axis of the fibre.

When the input wavelength λ is sufficiently different from the Bragg wavelengths defined by (2) – (3), the transmission T_x and T_y are nearly identical since they are unaffected by the presence of the grating. The PDL defined by (4) will then tend to zero. When the input wavelength λ approaches one of both Bragg wavelengths, the transmission along that polarization will be reduced strongly due to the grating. Equation (4) will then result in a PDL value tending to infinity. Finally, for a certain wavelength between both Bragg wavelengths, both transmission losses will be equal, leading to a zero value for the PDL. This leads to a double-peak PDL spectrum, which is illustrated in Figure 3. It is also shown that the power of the (total) transmitted light does not indicate the birefringence of the fibre, though clearly visible in the PDL spectrum.

In [5], it was shown that the PDL technique is capable of measuring transverse loads much sooner than is the case with traditional amplitude measurements. It is stated that in the performed experiments, peak separation only became visible in amplitude measurements at transverse loads of 300N and higher (Figure 4). By measuring the PDL peak power however, loads between 0N and 250N could be detected with a sensitivity of approximately 0.02 dB/N (Figure 4). At loads around 300N, the PDL power saturates as both peaks start to become fully separated and detectable in the amplitude measurements. Out of these results, it is clear that PDL and traditional amplitude measurements can (and should) be used complementary. Amplitude measurements are well-suited for large transverse strain measurements or when

peak separation is already present. PDL on the other hand is far superior in the measurement of small transversal strains such as during composite curing cycles.

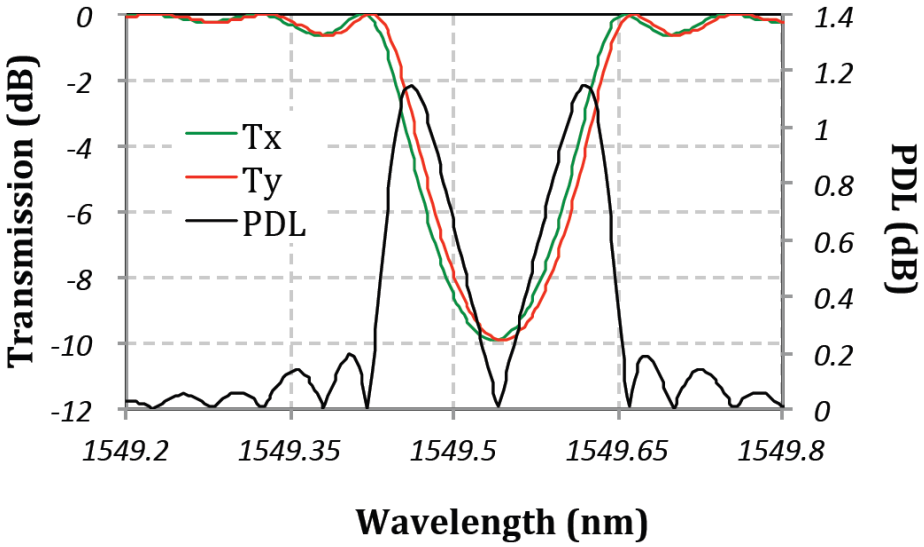

Figure 3: (top) simulated transmission spectra for both polarization axes; (bottom) PDL spectrum from the above-simulated spectra.

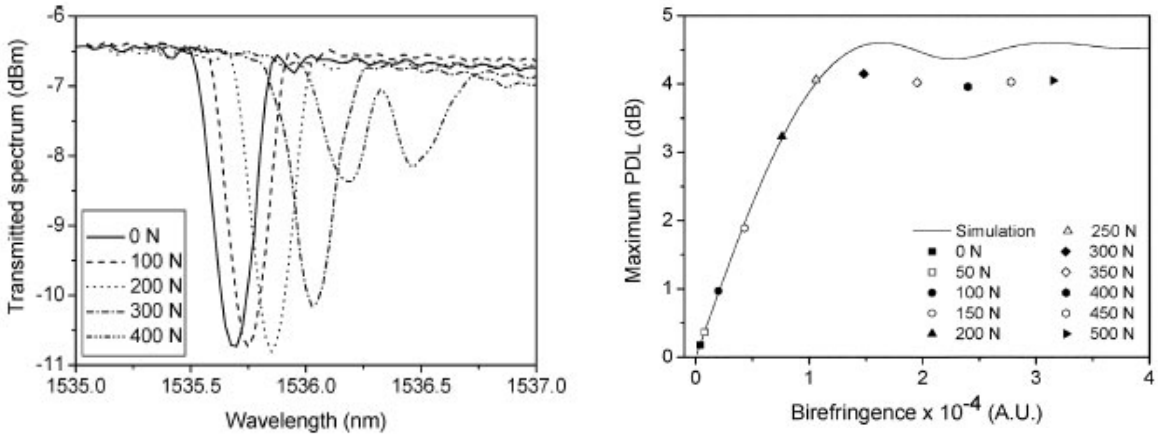

Figure 4: (left) Amplitude transmission spectra during transverse loading, (right) PDL peak power for different transverse loads [5]

3. Materials and methods

3.1. Test samples

In order to show the feasibility of the PDL technique towards transverse residual strain sensing, a set of carbon fiber reinforced polymer (M55J/M18) samples was created. The sample was 250mm x 125mm wide (Figure 5, left). This allows for 4 optical fibres to be embedded, with spacing of 25mm between each fibre, and a margin of 12.5mm at each edge of the sample. Each fibre contains a uniform FBG (8 mm in length, λ_B = ~1550 nm), written into hydrogen-loaded photosensitive single-mode fibre (PHOBDCDC15 from POFC), which is positioned in the middle of the sample. The coating of the optical fibres was chemically stripped along a few centimetres at the location of the FBG to keep a relatively high sensitivity in the transverse direction [6]. Teflon tubing was placed over the fibres to protect the egress points. The lay-up was deliberately chosen to be a cross-ply laminate $[0_2,90_2]_{2s}$ since this lay-up creates a strong difference in transverse strains. After lay-up has finished, the sample is vacuum bagged and put in the autoclave (Figure 5, centre and right).

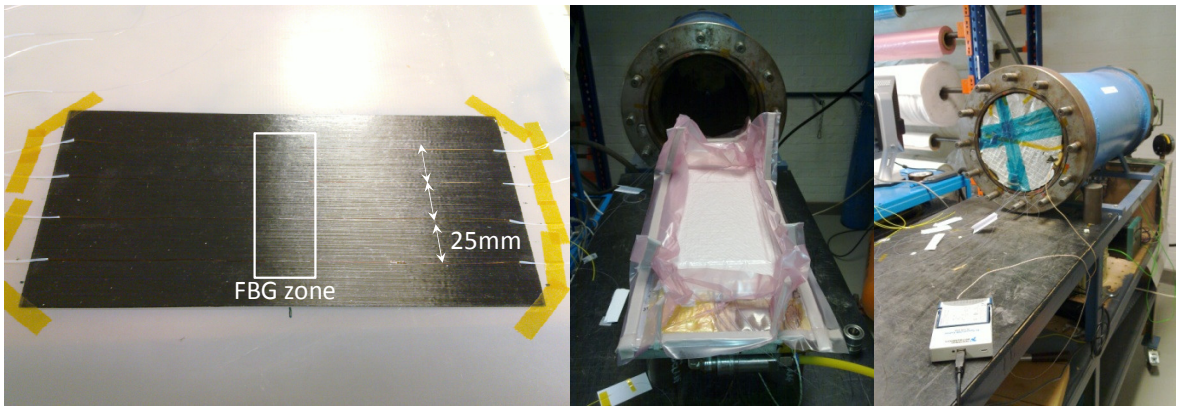

Figure 5: Embedding and manufacturing procedure of optical fibres in carbon fibre prepreg: (left) four optical fibres aligned to the reinforcement direction, (centre) Vacuum bagging the test sample, (right) closure of the autoclave.

3.2. Test set-up

The set-up to interrogate the FBGs is presented in Figure 6. All measurements were carried out using the optical vector analyzer CTe from Luna Technologies with a 3 pm wavelength resolution to follow the evolution (amplitude and PDL) of the FBGs in transmission. An optical coupler and an optical switch give us the possibility to consequently scan several sensors. A thermocouple was placed in the sample to obtain the temperature in situ. The laminates were cured in an out-of-autoclave fashion using vacuum bagging and a temperature cycle suited for the prepreg material. For practical reasons (outcome of the optical fibres of the autoclave) we chose to omit the external pressure cycle. The cure cycle is given in table 1.

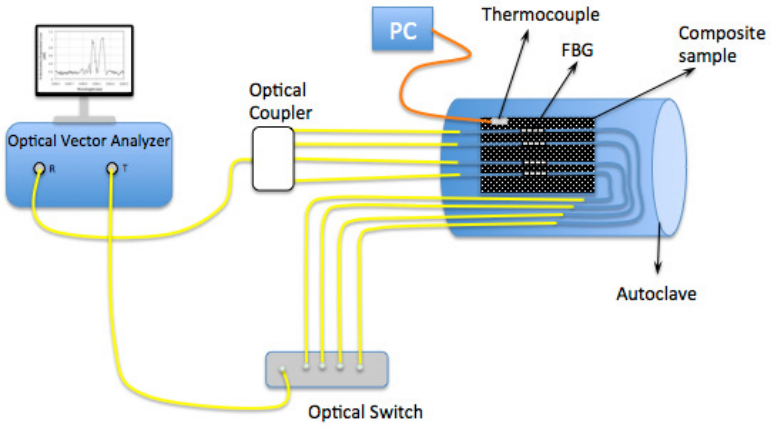

Figure 6: Schematical test set-up

	Step	***Information***
1	Heating	Room temperature to 120°C at 3°C/min
2	1st plateau	20min at 120°C
3	Heating	120°C to 180°C at 3°C/min
4	2nd plateau	100min at 180°C
5	Cooling	Non-forced cooling

Table 1: Curing cycle parameters

4. Experimental results and discussion

In Figure 7, the evolution of the FBG peaks is shown using the default Bragg peak wavelengths (dots), as well as for using the more sophisticated PDL technique (full lines). It

can be seen that, using default peak determination method, it takes 6 hours before the peak splitting becomes detectable. Before that time, the amplitude measurement detects only a "fake" averaged peak value using a centre-of-gravity algorithm [7]. The PDL on the other hand is capable much sooner of detecting peak separations. The average of both PDL peak wavelengths corresponds to the applied temperature cycle. Five zones can be detected which are in accordance with the five steps of the cure cycle (See table 1). In zone 4, we notice a small drop of the wavelengths which either can be linked with the occurrence of residual strains during the polymerization or with a cooling down phase after the exothermic reaction of the polymerization. Further research and analysis are needed to provide a clear answer.

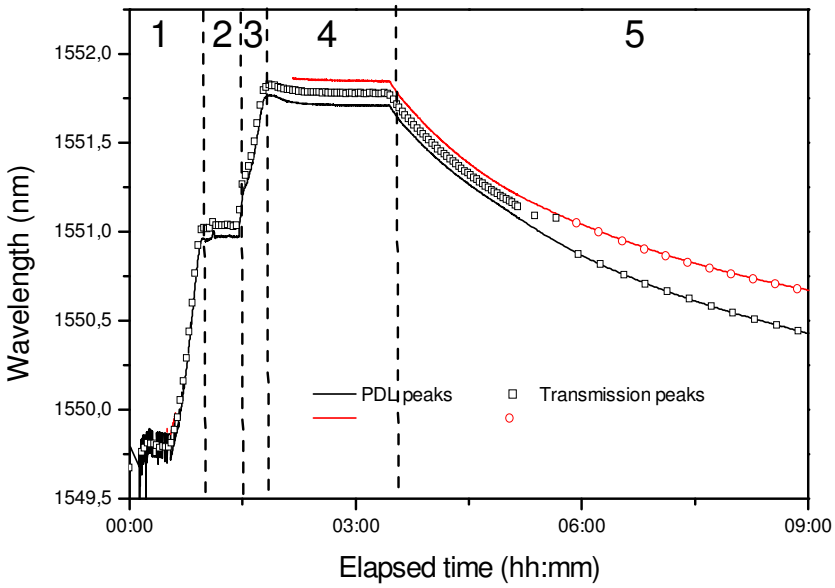

Figure 7: Bragg peak wavelength and PDL evolution during curing

However, notice that by subtracting equation (3) from (2) a temperature independent measure for transversally applied residual strains is obtained. Essentially, this means that we can use the peak separation of the PDL peak measurements as a measure for residual strains. In Figure 8 an estimation of the measured transversally applied residual strain is given. Approximately 800 µstrain is induced in the material in the transverse direction which mainly occurs during the cooling down phase of the material.

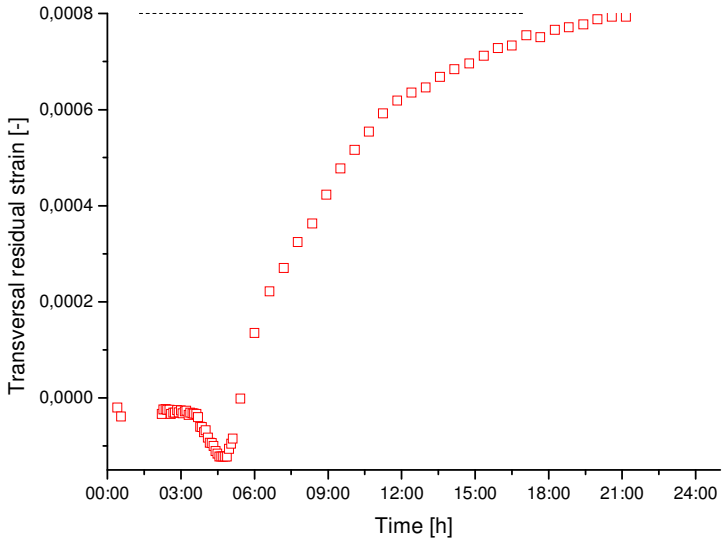

Figure 8: Evolution of transversally induced residual strains ($\varepsilon_2 - \varepsilon_1$) using the PDL technique.

Note that the strains found, are those found in the core of the optical fibre. In order to determine the strains in the composite structure, a transfer coefficient matrix method needs to be used [8]. In future work, the measurements of the PDL peak separation can be supported with the measurements of the PDL peak power, which is, according to [5], the most sensitive parameter in a PDL measurement. Although more sensitive, notice that a change in the light coupled into the fibre can already lead to a 'false' measurement.

5. Conclusions

In this paper the authors have introduced a new measurement technique to overcome the shortcomings of present conventional measurement techniques using Bragg peak wavelength measurements (with FBGs written in low and highly birefringent fibres). The technique which uses the polarization dependent loss of optical fibres was first introduced in the paper and afterwards used in an attempt to estimate the transversally induced residual strains of a carbon/epoxy composite during its production cycle. Approximately 800µstrain was measured in the core of the optical fibre after completion of the production cycle. We can conclude that PDL measurements are of added value for traditional Bragg peak wavelength measurements when small transverse strains need to be detected. The current developments in PDL measurements only allow measurement rates in the range of 1Hz. It is therefore (currently) limited to static measurements such as cure monitoring or other slow processes.

6. Acknowledgements

UGent acknowledge the funding by the European Union within the FP7 – SmartFiber project. UMons acknowledge the European Regional Development Fund and the Wallonia (Mediatic project) as well as the Interuniversity Attraction Pole of the BelSPo photonics@be. C. Caucheteur is supported by the F.R.S.-FNRS.

7. References

[1] Luyckx, G., W. De Waele, J. Degrieck, W. Van Paepegem, J. Vlekken, S. Vandamme, and K. Chah, Three-dimensional strain and temperature monitoring of composite laminates. *Insight*, **49**(1): p. 10-16.(2007).

[2] Voet, E., *In-situ deformation monitoring of aerospace qualified composites with embedded improved draw tower fibre Bragg gratings*., Ghent University. Faculty of Engineering and Architecture, (2011).

[3] Chehura, E., C.C. Ye, S.E. Staines, S.W. James, and R.P. Tatam, Characterization of the response of fibre Bragg gratings fabricated in stress and geometrically induced high birefringence fibres to temperature and transverse load. *Smart Materials & Structures*, **13**(4): p. 888-895.(2004).

[4] Hentschel C., S.S. *PDL Measurements using the Agilent 8169A Plarization Controller*.

[5] Caucheteur, C., S. Bette, R. Garcia-Olcina, M. Wuilpart, S. Sales, J. Capmany, and P. Megret, Transverse strain measurements using the birefringence effect in fiber Bragg gratings. *Ieee Photonics Technology Letters*, **19**(13-16): p. 966-968.(2007).

[6] Voet, E., G. Luyckx, and J. Degrieck, *Response of embedded fibre Bragg gratings: strain transfer effects*. in "*Proceeding of OFS 20*", Edinbrugh, UK, (2009).

[7] Negri, L., A. Nied, H. Kalinowski, and A. Paterno, Benchmark for Peak Detection Algorithms in Fiber Bragg Grating Interrogation and a New Neural Network for its Performance Improvement. *Sensors*, **11**(4): p. 3466-3482.(2011).

[8] Luyckx, G., E. Voet, W. De Waele, and J. Degrieck, Multi-axial strain transfer from laminated CFRP composites to embedded Bragg sensor: I. Parametric study. *Smart Materials & Structures*, **19**(10): p.1-9 (2010).