Authentication of Czech Banknotes using Raman Microscopy

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***Abstract*—At the present time, all modern banknotes contain security features to prevent their counterfeiting. Some of these features include special paper and inks with a specific composition as well as tints that are hard to reproduce by commercial copiers and printers. Current availability of digital technologies makes it much easier to produce higher quality counterfeits than in the past. This paper is focused on systematical experimental examination of paper and inks used on Czech banknotes to obtain characteristic Raman spectra that serve for the authenticity assessment. Raman spectroscopy is a powerful method for material identification and meets requirements of the forensic examination. This method has the potential to recognize various substances, even their structural modification. On the basis of Raman spectra, it is possible to determine whether the questioned banknote is genuine or a forgery, even though the specific composition of inks is a manufacturing secret. Raman spectral data of the investigated Czech banknotes were used for creation of a spectral library for the purpose of further verification of questionable banknotes.**

Keywords-authenticity; Czech banknotes; Raman sepctra; inks; spectral library.

I. INTRODUCTION

Banknotes are used worldwide as universal mean of payment. Also, the desire of self-enrichment is a sentiment found all over the world. The desire to become rich is sometimes accompanied by illegal activities, including forgery of money. Creating and using counterfeit money is one of the oldest crimes in history. Current popularization and availability of digital technology shifts the level of counterfeits at a higher level and it is much easier to produce counterfeit money than it was in the past.

To prevent counterfeiting banknotes, all the modern banknotes contain different amounts of more or less successfully falsifiable security features. Many of them are recognizable to the naked eye as safety watermarks, key register line or hidden diagram. Some can be verified using ultraviolet (UV) light or chemical reaction of a special pen with the banknote paper, but some require more advanced analytical tools where a naked eye is not sufficient as a detector. Understandably, it is much more difficult and demanding to falsify these kinds of advanced security features.

In this paper, the term "banknote" refers to currency bills i.e. money, but could also be used in a broader sense, to include different valuable documents, cheques, travel tickets, stamps, vouchers, shares, etc.

Raman spectroscopy/Raman microscopy is an innovative analytical tool that has become a valuable part of laboratories all over the world lately [1]. This potential method allows an insight into the structure of materials on a molecular level and enables evaluation of their composition based on the characteristic molecular vibrations caused by incident monochromatic light. Raman spectroscopy is a powerful tool for material identification. Applications of Raman spectroscopy comprise increasing number of scientific and technical fields in recent years. We mention some examples in the following fields: material sciences [2], nanotechnology [3], chemistry [4], pharmaceutical industry [5], food technology [6], biology [4], medicine [7], arts and cultural heritage [8], as well as forensic analysis [9] and security [10].

Raman spectroscopy is an effective tool for rapid identification [9]. The key importance for the identification is a highly specific chemical "fingerprint" in form of Raman spectrum for every individual chemical element or its modification. Raman spectra reflect vibrations of bonding in the structure after laser irradiation and are unique. Essentially, it is analogical to the human fingerprints. The method fulfils the requirements for forensic examination. It is also non-destructive, non-invasive and applicable to a wide range of substances. Specifically, for the application presented in this paper it means, that researched banknotes may be after analyzing, if genuine, return back into circulation.

Apart from the common methods used for counterfeits detection suggestions for other innovative approaches to banknotes control and confirmation of their authenticity have been proposed in the recent years. L.S. Eberlin et. al. [11] use ambient mass spectrometry for chemical analysis of banknotes to obtain characteristic chemical profiles for genuine banknotes and for counterfeits. This method meets requirements of non-destructive, instantaneous, reproducible measurements. G. S. Spagnolo et. al. [12] use a new approach to verify banknotes originality based on the idea of hylemetry, a methodology conceptually similar to biometry applied to non-living matter. Specifically, the random distribution pattern of the metallic security fibres set into the

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paper pulp is dealt in the paper. C. Nastoulis et. al. [13] propose a new method useful for banking systems around the world for the different banknote recognition using probabilistic neural network.

The rest of the paper is structured as follows. The scope of the research is outlined in Section 2. In Section 3, the Czech banknotes are introduced together with some statistics of counterfeits since 2008 and brief overview of the methods used for counterfeits detection. Section 4 describes the fundamental principle and features of Raman microscopy, the studied method applied to detect counterfeit banknote. The results of Raman analyses are then discussed in Section 5. The conclusion and future work is presented in Section 6.

II. Scope Of The Research

The possibility of the authenticity assessments of Czech banknotes has been investigated using fundamental features and advantages of Raman microscopy. Both genuine Czech banknotes and their counterfeits were studied on the basis of the material composition characteristic for their manufacture. Analysis of the used materials can be conducted in order to confirm counterfeit currency. For the purpose of relatively rapid evaluation of spectral data of examined banknotes the database of Raman spectra of paper and inks used on Czech banknotes was created.

III. Czech Banknotes

There are six banknotes currently in circulation in the Czech Republic, valid since 1993 when Czechoslovakia was separated into two individual countries.

Figure 1. Overview of the valid Czech banknotes.

The nominal value of these banknotes are 100 Czech koruna / crown (CZK), 200 CZK, 500 CZK, 1000 CZK, 2000 CZK and 5000 CZK, all the banknotes are displayed in Figure 1. In addition, there used to be two other valid banknotes, in the value of 20 CZK and 50 CZK, which were withdrawn from circulation in 2008 and 2011, respectively, and were replaced by coins only. The author of all Czech banknotes is Oldrich Kulhanek (1940 - 2013), Czech painter, graphic and stage designer, illustrator and pedagogue.

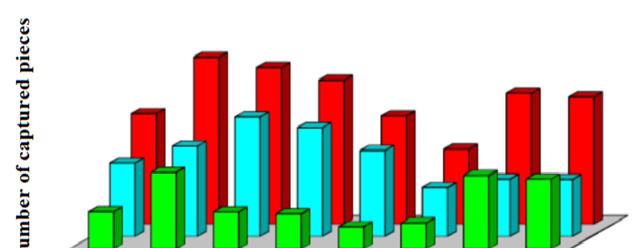
Czech banknotes and coins are very safe in comparison with other international currency. The development and application of protective elements on Czech banknotes are some world leaders. The 1000 CZK banknote with innovative security features was awarded the title Banknote of the Year in 2008 [14] by The International Association of Currency Affairs. This was an acknowledgment of the quality of Czech banknotes as being among the highest in the world, not only in terms of artwork but also in the technical level of protective elements applied. This was the third award of the Czech currency since 1993.

A. Statistics of Counterfeits

The occurrence of counterfeits of Czech Banknotes has been decreasing since 2008 according to the Czech National Bank (CNB) and as seen in the graph in Figure 2. Nevertheless, 2,383 banknotes in the cash value 2,355 million CZK were captured in 2015. The most often faked in recent years are 1000 CZK (57.2 % in 2015) and 500 CZK (17.89 % in 2015) banknotes [15].

Absolutely predominant (96.6 % in 2015) forgery technique for the Czech currency in a long term is inkjet print. Colour copying was used for 3.3 % of fakes revealed last year. On the other hand, the most often forgery technique used on Euro banknotes captured in the Czech Republic in 2015 was offset print for 52.8 %, which is not almost used on CZK banknotes fakes (only 0.1 %), followed by inkjet print for 46.6 % of counterfeited Euro. The situation was similar with the US dollars, with 98.3% of counterfeits using offset print.

On a five-grade scale of danger (1 very dangerous - 5 primitive) the highest degree for CZK banknotes (89 %) is



	2008	2009	2010	2011	2012	2013	2014	2015
Foreign	1550	3190	1543	1461	928	1085	3063	2918
CZK	3062	3765	4986	4541	3586	2045	2398	2383
Total	4612	6955	6529	6002	4514	3130	5461	5301

Figure 2. Occurrence of counterfeits of Czech Banknotes and EURO banknotes in the Czech Republic from 2008 to 2015 [8].

4th degree (less successful), 5th degree (6 %) followed by 3rd (4 %). Even the number of counterfeit banknotes of 2nd degree (dangerous) decreased from 21.8 % for all Czech falsified banknotes in 2011 to 0.1 % in 2015 [15]. Counterfeits of Euro banknotes seized in the Czech Republic are much more likely (than Czech banknotes) to be ranked 2nd (6 %) and 3rd (51 %) degree of danger. Counterfeit US dollar banknotes seized in the Czech Republic mainly fall into the 3rd degree of danger category (98 %) [16]. The quality of CZK counterfeits compared to Euro and US dollar counterfeits underlines good technical quality of protective elements of Czech banknotes.

B. Methods for counterfeits detection

There are various methods and techniques known for testing authenticity of banknotes. Firstly, simple methods to verify visible elements are used, such as watermark lamps, intaglio print, microtext, UV luminescence or holograms. Secondly, more sophisticated methods are used, which require special equipment for verification, not only naked eye, and are usually based on the colour response of banknote’s features analysis. These methods include Magnetic Ink Scanners, isocheck, Fibre-Based Certificates of Authenticity or colour analyses.

Generally, it is not possible to say which method is the best. Usually, a combination of more methods gives better results and confirmation.

Generally the process of control of the authenticity of banknotes could be summed up into four steps:

1. checking of the paper – unique feel of the paper
2. checking of the print quality – sharp and clean lines
3. checking security features on the banknote
4. comparing with the banknotes of the same series

IV. Raman Microscopy

Raman spectroscopy, as a modern spectroscopic method, has, in principle, the potential to answer a number of questions concerning chemical details of a molecular structure. This feature makes Raman spectroscopy suitable for material identification [1].

The method is based on the Raman effect, an inelastic scattering of photons on molecules. The majority of incident photons is scattered elastically (Rayleigh scattering), only a very small part (approximately 1 of ten million photons) needful for origin of Raman spectra is scattered inelastically. This fact requires precise instrumentation to ensure conditions for accurate measurements. Analysis possibilities are extended when using the advantages of optical microscopy via a coupled microscope.

Raman spectroscopy brings advantages over other techniques as non-destructiveness, no special requirements for sample preparation, rapidity, applicability to all states of matter and different forms, measurements through covering layers or contactless measurements. The listed features make this analytical tool convenient, attractive and participating on the growth of its popularity and applicability worldwide.

The greatest drawback of the method is occurring of luminescence which as much stronger quantum effect may overlap Raman spectra and mask spectral information. Another disadvantage is eventual degradation of a sensitive sample when using intense laser beam [17], [18].

V. Experimental Part

All types of Czech banknotes were analyzed by Raman microscopy. The procedure is demonstrated on 200 CZK banknote in this paper, however the same routine was applied on all banknotes. On each banknote, 23 points were picked, both on the face and the reverse side. The performance criterion consisted in a color layout and also in the distribution of different printing techniques used during the production of the banknotes and the application of protecting elements.

The most important aspects of the banknotes analyses using Raman spectroscopy were the used inks and paper. To study the diversity of the results two types of banknotes imitation were created – by the inkjet printer and by color copier. These are the most often used methods in the Czech banknotes counterfeiting.

A. Inks

For obvious reasons, the specific composition of inks used on banknotes is not publically known. Using Raman microscopy does not suffer from an absence of this specific information although this manufacturing secrets. Original banknotes provide corresponding data which serves as the standard for comparison. Colours occurring on all banknotes together with the number of protective elements are listed in Table 1.

TABLE I. INKS AND SECURITY FEATURES ON BANKNOTES

Value [CZK]	*No. of measured points*	*Inks - colours*	*No. of security features*
100	23	green, red, yellow, black	6
200	23	brown, orange, green, black	6
500	23	brown, yellow, red, ochre, green, black	7
1000	23	violet, ochre, pink, blue, black	8
2000	23	green, violet, yellow, pink, black	8
5000	23	blue, red, yellow, pink, black	8

B. Paper

Banknotes are printed on special high quality paper. This paper is based on cotton, contains a mixture of chemical additives, also characteristic fibers (several mm long) and watermarks to prevent the imitation. More stringent requirements are laid on this paper in comparison with ordinary consumer paper made of wood fibers. Banknote paper must have greater strength and flexibility, must be resistant to bending, breaking and tearing. Czech banknotes are printed on natural colored paper. This means that the paper is not pure white, but has a very light ochre tint.

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One of the easiest ways of fake's recognition is its sound of wrinkling or friction (the acoustic safety feature). It is influenced by appropriate composition of the paper fibers. The paper banknotes sounds differently than writing paper, the sound is tougher.

C. Measuring Device

InVia Basis Raman microscope from Renishaw was used for recording all Raman spectra. Argon ion laser with the excitation wavelength 514 nm in visible area (VIS) and maximum output power of 20 mW and 785 nm near infrared (NIR) diode laser with maximum output power 300 mW were used as light sources. A Leica DM 2500 confocal microscope with the resolution up to 2 µm was coupled to the Raman spectrometer.

All measurements were collected at magnification 20x or 50x, with 15 s exposure time, 10 accumulations. Powers of lasers were from 0.1 % to 5 % of the output laser power. The samples were scanned in range 200 to 3200 cm^{-1} with 2 cm^{-1} spectral resolution.

D. Results

Czech banknotes and their imitations were measured using both lasers (VIS and NIR). Some of the inks exhibited luminescence and their Raman spectra were poor quality or were not possible to acquire by laser from the visible region. Therefore, most of spectra were acquired by NIR laser. High level of luminescence was also present at imitations. This behavior is also a partial result indicating the presence of luminescent element which is missing in the spectra of original banknotes.

The layout of the inks is typical to the used printing method hence microscope view can satisfactorily prove the forgery in many cases.

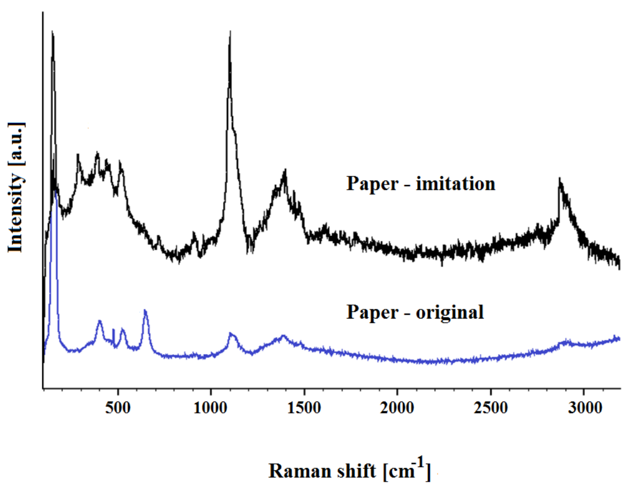

Figure 3. Raman spectra of banknote and ordinary office paper.

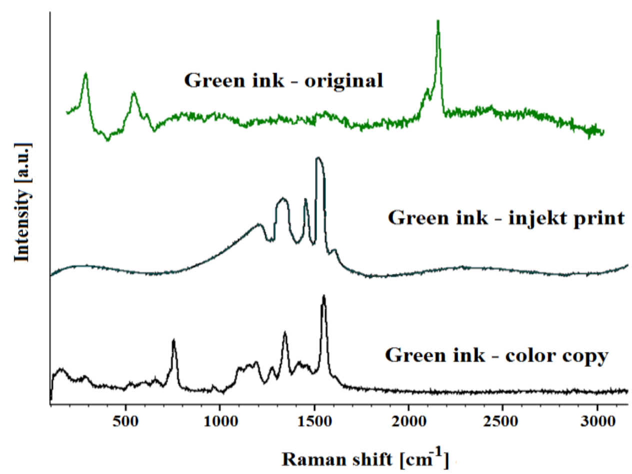

Figure 5. Raman spectra of green ink on genuine 200 CZK banknote and its two imitations.

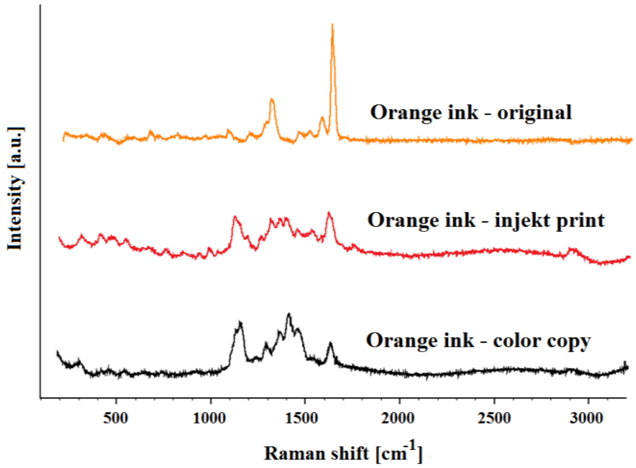

Figure 4. Raman spectra of orange ink on genuine 200 CZK banknote and its two imitations.

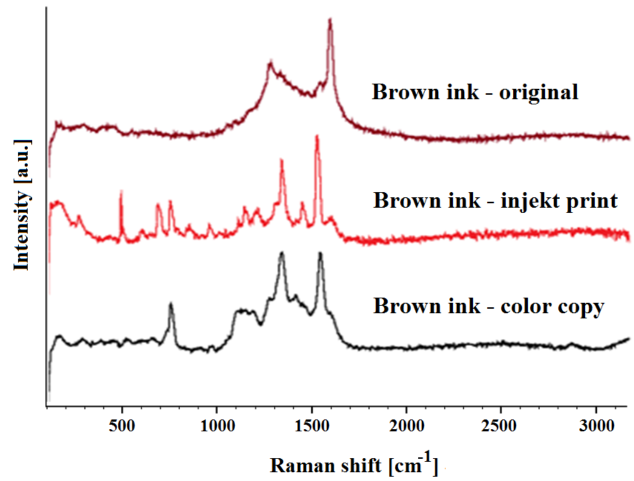

Figure 6. Raman spectra of green ink on genuine 200 CZK banknote and its two imitations.

Spectrum of paper confirms the presence of viscose fibers recovered from cellulose that are similar in structure to fibers of cotton from which are divergent mainly by the presence of the peak at 650 cm^{-1} for C-S-C vibrations [19]. This peak is missing from the spectrum of ordinary paper. Raman spectra of banknote paper and ordinary office paper used for imitations are displayed in Figure 3.

In some measured points not only a spectrum of an ink but also spectral response of the paper can be observed. In these cases the spectrum of paper of the banknote is for further processing of spectral data in spectral library subtracted from the measured Raman spectrum.

The diversity in layout of characteristic peaks for different colours can be seen in Figure 4 to Figure 6.

Noticeable differences in Raman spectra are recorded for genuine banknotes and reproductions as is shown in Figure 4 to Figure 6 for orange, green and brown ink on 200 CZK banknotes. Different layout of Raman peaks and their intensities clearly demonstrate various compositions of used inks.

VI. Conclusion and Future Work

Based on characteristic Raman spectra of banknote materials, paper and inks, the authenticity assessment of Czech banknotes was presented. Raman spectroscopy was used as an innovative tool for analyzing Czech banknotes in this sense. The features examined have characteristic Raman spectra and provide information about the authenticity of banknotes and point out any successful forgeries, which are not possible to distinguish with the naked eye. For the purpose of further verification of banknotes, the Raman spectral library of inks measured on all Czech banknotes using lasers from visible and near infrared region was created.

A similar routine was applied on selected Euro banknotes and the results show universality of the use of Raman microscopy for the purpose of banknotes originality assessment.

The future work within the research will be focused on measurement of Czech banknotes issued in all the years to have a complete reference data for the Raman spectral library.

Acknowledgment

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