Plastic Banknotes

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Australia's Plastic Banknotes: Fighting Counterfeit Currency

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diffraction gratings · history of science · plastic banknotes · polymers

Introduction

The need for banknotes in modern society is often questioned. Even with the development of electronic banking and credit cards we still live in a society that needs cash. In 1966, Australia converted from the Imperial system of banking, that is, pounds, shillings, and pence, to a decimal system. To mark the occasion, the Reserve Bank of Australia (RBA) issued a brand new, highly attractive set of notes. These notes were state of the art in terms of their security and resistance to forgery attempts. However, it took less than a year for the forgers to attempt to pass the first counterfeited (forged) $10 note. It needs to be realized that the forger does not have to reproduce the note accurately; simply produce a simulation which is acceptable for at least one transaction. In the case of the 1967 forgery, ordinary paper purchased at a regular office equipment outlet was used, and simple office equipment which they had modified in quite an ingenious manner was used to produce the notes.

The Governor of the RBA at the time, Dr. H. C. (Nugget) Coombs, was understandably quite concerned that the security in Australia's banknotes (which at that stage was the best available world-wide) had been so easily and so quickly simulated. His vision was to start the project that this Essay describes. He had decided that science should be able to put a bigger distance between what the forger was so easily able to simulate and what the RBA could produce. So at his direction, the Reserve Bank organized a preliminary meeting in Melbourne. Before discussing this meeting a brief history is helpful in understanding the world of the forger and the challenges that would be faced by the scientists.

Banknotes: A Brief History

Replacing bulky, heavy coins with light paper money has been claimed to be one of mankind's greatest inventions of the last 1000 years. The Chinese issued the first paper banknote in AD 1024. They used a special "paper" made from mulberry bark and their printing was equally elaborate and consisted of six wooden blocks, each with its own unique design. Blue dyes were used to produce a distinct effect. Banknotes were so readily accepted by the Chinese that 100 years later over 70 million were in circulation.

The use of banknotes in Western society did not become widespread until the 16th century when the goldsmiths, who had extensive vaults for the safe keeping of their precious metals, gold, and silver, began to accept deposits and gave "receipts". With time these "receipts" became tradable and eventually led to the development of banknotes.

Counterfeiting and Forgery

Counterfeiting, whose beginnings go back centuries before banknotes, has been called "the second oldest profession". The advent of banknotes was welcomed by counterfeiters; it was a far more profitable business than reproducing coins or works of art and had a wider population or "market" for their products. Indeed since most banknotes cost little to produce, the successful passing of a forgery is virtually all profit.

The Reserve Bank of Australia's first line of defense against forgery is the general public. In each transaction the receiver of the note is expected to examine the banknote carefully and be satisfied that it is genuine. This "person in the street" recognition is a cornerstone in the Reserve Bank of Australia and other central banks' strategy to beat the forgers. If you accept a forgery then you are the loser.

Penalty for Forgery

All societies regard forgery as a most serious crime and in past eras the penalty for forgery was similar to that for murder. Indeed some previous banknotes had printed on them that anyone caught counterfeiting the note would be beheaded. Most Western societies have relaxed this penalty. However, in China the statutes still allow for the death penalty.

There are a number of reasons why society considers forgery such a serious crime. Historically, banknotes carried an image of an Emperor or Head of State, and it was considered treason for a commoner to forge their portrait.

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This is of less significance today although some Asian countries still consider this a hanging offence. More importantly, the State suffers a financial loss from the loss of seigniorage, which is the difference in the face value of the note and the production cost. For example, a $100 note costs only a few cents to produce so the State, in effect, suffers a $100 loss for each forgery it pays out on. Finally, forgery has been, and still is, used as a weapon of war or conflict between nations. The most famous, or notorious, example of this was Nazi Germany's forgery of the Allies' currency during World War II. This massive forgery was code-named "Operation Bernhard" by the German SS and the aim was to flood the British and American economies with quality forgeries to disrupt their day-to-day operations and hence their war effort. The Germans used the skills of the inmates in concentration camps to produce printing plates and also provided the necessary printing equipment to produce excellent forgeries. They could only be detected by "frivolous inspection using a magnifying glass". Towards the end of the war, the Germans were producing 500 000 British notes a month. Fortunately the war ended before "Operation Bernhard" was fully implemented but the German SS did use some forged notes to buy war equipment from neutral countries and to pay British spies. The upshot was that after the war Britain had to reissue its currency because of the few "Operation Bernhard" notes in circulation.

"Operation Bernhard" was apparently Adolf Hitler's very own idea but he was not the first to use forgery as a weapon of war. In 1470–1476, Milan sought to undermine the Venetians by forgery, and Frederich the Great used counterfeit notes during the Seven Years War. The British, during the American War of Independence, counterfeited Continental currency and Napoleon forged Austrian and Russian notes to buy food and equipment during his European campaign. There are numerous other examples where governments have used counterfeiting in an attempt to destabilize the enemy and only a few selected examples have been mentioned here.

Forgeries by governments use massive technical resources and are difficult to counter. Given sufficient technical resources it is possible to make quality, difficult to detect, forgeries of most, if not all, banknotes. Fortunately most forgeries are carried out by small groups with limited resources. Forgery involving governments needs to be addressed at the political level.

Simulation not Reproduction

The perfect forgery has never been detected! The forger does not need to reproduce the actual note, but instead only produce a simulation that can be passed at least once. The forger does not need to worry about durability but must make a number of compromises dictated by the resources and skills available.

Banknotes, from those first issued by the Chinese through to when Australia's first plastic note was issued in 1988, challenged the forger in two technical areas; the substrate, and the printing and design. Forgers usually find it difficult or impractical to produce a simulation of banknote paper, which has evolved considerably over the years. These days banknote paper is made of cotton fibers and is referred to as rag paper. It contains various security features which are introduced during the manufacturing process. These features include a watermark or emboss, metallic threads or particles, and other unique features, all of which are introduced during the formation of the paper from a water slurry. In recent times, even plastic stripes have been incorporated. Minor changes and improvements continue to be made to security paper for banknotes but it is a mature science and as we will see, techniques to simulate the paper are available.

Ink and printing processes have also made significant progress over the years. Perhaps the most significant is the so-called intaglio printing. This requires expensive equipment which is rarely available to the forger. In simple terms, ink is wiped into the engraved pattern of a large cylinder. The depth of these engravings is considerable so that when the cylinder contacts the paper under high pressure the ink transfers and forms a raised image. This gives the raised print and hence the characteristic feel of traditional banknotes. The banks relied heavily on this to give them an advantage over the forgers. It, along with the unique paper, was the security in the 1966 Australian banknotes, the $10 note is shown in Figure 1. On the other hand, the making of printing plates is now relatively simple and not restricted to a few skilled tradesmen as in the past.

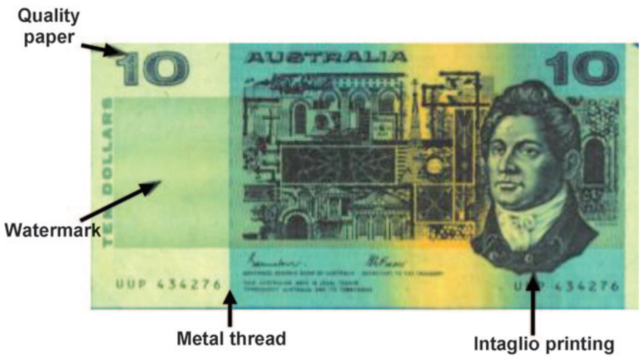

Figure 1. Australia's paper $10 note showing the security features.

1967 Forgery of the Australian $10 Note

In Australia, the $10 note forgery of 1967 was very good. In fact, in a number of instances those familiar with banknotes have difficulty distinguishing the forgery from the authentic notes. The instructions issued by the RBA to the public on how to identify a forgery were very telling; check the serial number. This was because the forger, for technical reasons, could only produce a limited series of numbers. It was of great significance that the RBA did not consider their prime security features, that is, watermark, metal thread, or intaglio print, to be appropriate for the detection of the forgeries.

However, in 1967 when the forgers were set to pass their notes, last minute doubts about the feel of the notes (the result of no intaglio printing) caused the forgers to spray the notes with a wax film. The forgers then attempted to pass the notes but a shop assistant was unhappy with the feel of the presented note and hence they were caught. Nevertheless by

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this time over $100 000 worth of the forged $10 notes had been collected by the authorities and over 1500 forgeries had been successfully passed in the state of Victoria alone. This was the tip of the iceberg and indicated the massive scale of this forgery.

Lessons from the past as well as the experience of the Australian 1967 forgery gave some guidance on how to proceed with the development of a new banknote. Forgery gangs often operate with "wholesalers", who produce the forgeries, and "retailers" who buy the forgeries and then "pass" them. Application of the wax coating by the "retailer" was a foolish move, but it illustrates that the more people involved in the forgery chain, the greater the chance of detection—someone will make a mistake. Hence complex technology, which forces the "wholesalers" in the forgery chain to use a wide range of skills, is desirable. Also since production of genuine banknotes is a high volume process it is possible for the banks to use expensive operations.

As we will show in this Essay, potential forgers would be required to have knowledge of polymer properties (preparation, processing, and printing), an understanding of replication techniques, and some insight into the chemistry/physics behind the optically variable devices (OVDs). Thus they would be forced to turn away from the usual combination of rag paper, printing plates, and a printer, and the chance of detection with such a wide diversity of necessary skills increases. Added to this, of course, was the much higher level of science in the new polymer banknotes. However smart science is of little value if the public can't recognize or see what it does.

Development of New Polymer Banknotes

Presentation of the Problem by the Reserve Bank of Australia

After the 1967 forgery Governor Coombs, through his scientific liaison officer, instigated a meeting with senior members of the Australian scientific community. The invitations to this initial meeting indicated that the discussions were to be on "some aspects of banknote printing". The group met in 1968 where they were addressed by Governor Coombs—an important indication of the seriousness with which the Reserve Bank treated the discussion and the possible outcomes. There are a number of very important points to note about these original meetings. Firstly, the seriousness with which both the scientific community and the bank approached these meetings was apparent from the positions held by those attending: the scientists were generally Professors of university departments, and senior scientists from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The Governor also explained that the object of the meeting was to see if it was possible to devise techniques that produced banknotes which would be more difficult to forge.

However, whilst the RBA indicated there were no restrictions on the approach that might be taken, it was clear from the strong emphasis on scientists with a physics background and from the discussion, that the RBA was focused on more accurate printing. David Solomon was approached subsequent to this first meeting by the Chairman of CSIRO and David suggested the use of plastic papers. As a result David, along with a photographic expert, was invited to attend a "think tank".

At this meeting an interesting point was raised by the photographic expert, who countered virtually every suggestion of a new approach with "if you can see it, you can photograph it". The implication being, that if you can photograph it, then with color separation technology it would be possible to make printing plates and hence forge the notes. This comment struck a chord and challenged the scientists. Interestingly it was the two chemists present, Dr. Sefton Hamann and Dr. David Solomon, who responded to the challenge. Both worked together at CSIRO and they decided to investigate devices that could not be photographed and this in turn was to lead ultimately to the use of clear plastic film as the substrate to replace paper. Significantly, the project involved considerable physics, which was carried out in the Chemistry Divisions of CSIRO. It was an excellent example of those needing the solution to a problem also accepting the responsibility for the work.

The early meetings with colleagues at the RBA clearly showed their interest in optically variable devices (OVDs). They were always reluctant to move away from traditional paper because of an entrenched view that quality print was not possible on other (polymer) substrates. Hence it is convenient to first discuss the work on OVDs and then to consider other substrates.

Optically Variable Devices

Optically variable devices (OVDs) are defined as a device which changes its appearance when something external to the note is changed. For example, when the angle of viewing is altered, as the light intensity is changed, or the pressure or temperature is varied (by the fingers); all of these factors were investigated and are discussed below. OVDs would preclude the forger from reproducing the banknote by photographic printing plate technologies or print technologies and address the challenge to combat forgery by photographic means.

Gold Foil

Gold foil is possibly the simplest example of an OVD. Very thin films of gold appear gold colored in reflected light but green in transmitted light. Hence a forger would be forced to develop methods of producing very thin films of gold; this requires high vacuum equipment and transfer foil technology. Such thin films are economically feasible for use in banknotes; the amount of gold required is infinitesimal. An example of an experimental note is shown below (Figure 2).

However, if gold foil is used the note would need to be viewed in transmission, and this was a hint to the use of plastic or at least a laminate which could receive a plastic insert.

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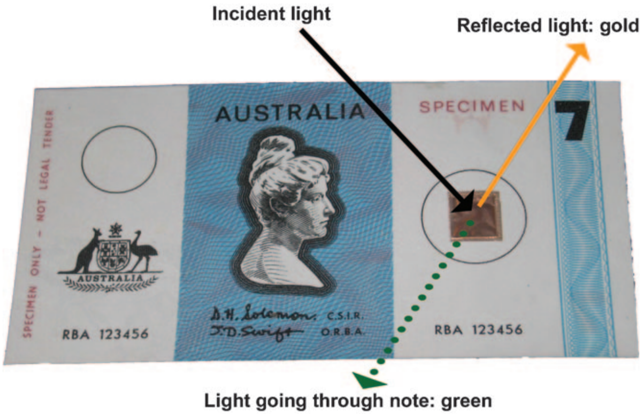

Figure 2. An example of gold foil used. The incident light is seen as gold when reflected and green when viewed in transmission.

Photochromic Compounds

Photochromic compounds are defined as compounds which change color with light. The idea was to have a part of the banknote which changes color when the note is taken from a (relatively) dark area, for example, wallet, purse, pocket, out into the ambient light. When the note is returned to the dark area then the color would revert back to the original.

Ideally a compound that is colored (e.g. blue) in the dark and colorless in the light was desired for long-term stability, but this proved difficult. A class of compounds known as spiropyrans was investigated; these compounds are white in the absence of light but rapidly turn blue even in diffuse light such as that given off by fluorescent tubes. Spiropyrans were not used in the final banknotes (Figure 3).

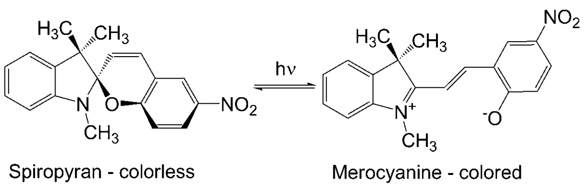

Figure 3. An example of spiropyran chemistry. The spiropyran form is colorless; on exposure to light it converts into the merocyanine form which is colored.

Diffraction Gratings and Moiré Interference Patterns

These devices rely on line patterns that give various light effects, and Sefton Hamann was responsible for developing the theory which was used to make the master diffraction grating and the Moiré interference patterns from which replicas were produced. These OVDs were extensively investigated and deserve a more detailed discussion.

Diffraction Gratings

Diffraction gratings are formed from line patterns in a substrate. Usually these line patterns, typically 12000 lines per centimeter, are coated with a very thin film of a reflecting metal (e.g. aluminum). Hence light is diffracted from the lines to give various colors which change as the grating is moved.

Preparation of Unique Master Diffraction Gratings

At the time this project was carried out (1967–1972) the commercially available diffraction gratings were either straight lines or spirals. In both cases the spacing between the lines was constant and the gratings were produced on mechanical ruling machines or in a lathe (Figure 4).

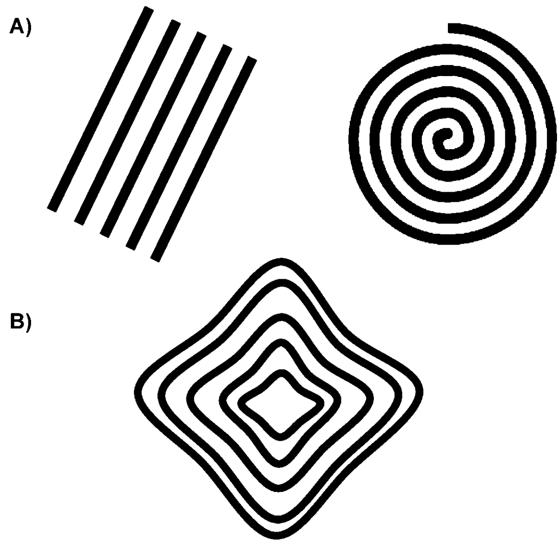

Figure 4. A) Some diffraction gratings that were commercially available in 1967–1972. They have uniform line shape and spacing. B) Butterfly pattern with variable line shape and spacing that was used as a trial for making unique diffraction gratings.

From the outset it was decided that diffraction gratings that were unique needed to be produced for security reasons, and to give the artist complete freedom in design. To satisfy these requirements, technology that would allow the production of diffraction gratings with any line pattern, and variable spacing between the lines was desired. The butterfly pattern shown in Figure 4 was suggested as a trial. There were two possible approaches to making the target grating; photographic reduction and/or electron beam lithography (EBX).

Photographic Reduction

The idea was to prepare a 65 × 65 cm drawing of the butterfly and then photograph this; the limited resolution, and the 25:1 reduction mean that a diffraction grating with about 1200 lines per centimeter could be expected. This was the diffraction grating used in early experimental notes. At this low line intensity the diffraction effect is not striking or brilliant, but the virtue of the photographic reduction was that

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it showed the RBA a complete process from design through to incorporation in the note. Also the principles could be applied to the EBX system when we would have access to an appropriate machine.

Electron Beam Lithography

The attraction of EBX was that it could produce a grating with the high line density, 12000 lines per centimeter, that was required, but the technique was unproven and not easily available. Technically the challenge was that the computer-controlled electron beam could only focus over an area of approximately 2×2 mm. As a grating of 25×25 mm was required, the stage had to be moved and in effect 144 small areas drawn. The major challenge was what is termed "butting" the lines, making sure they match up, each time the stage is moved.

Alan Wilson and David Solomon were given access to an EBX machine (JEOL-5A) for a two-week period in 1971. At the end of this time they had produced a small section of the target butterfly grating, thus demonstrating the feasibility of the concept. This accomplishment was carried out 11 years before holograms/diffraction gratings were used in credit cards and our team was frustrated by not being able to explore this market. Our agreement with the RBA precluded us from releasing technology that could adversely affect their later use in the production of banknotes.

Replication of Diffraction Gratings

In production a method was needed to replicate the valuable master diffraction grating and make sub-masters. To do this a number of techniques were used, including:

1. Embossing the master into a plastic. The plastic was heated to near its softening point, the diffraction grating pattern embossed into the plastic, and then a metal copy grown by electroplating techniques.
2. Direct copying of the master by electroplating.
3. Making replicas in epoxy resins.

Importantly, embossing into plastic film was quite successful. It could be done with the commercial gratings as they were supplied in a plastic film with a high softening point. A wide variety of different gratings were made, some of which are shown in Figure 5.

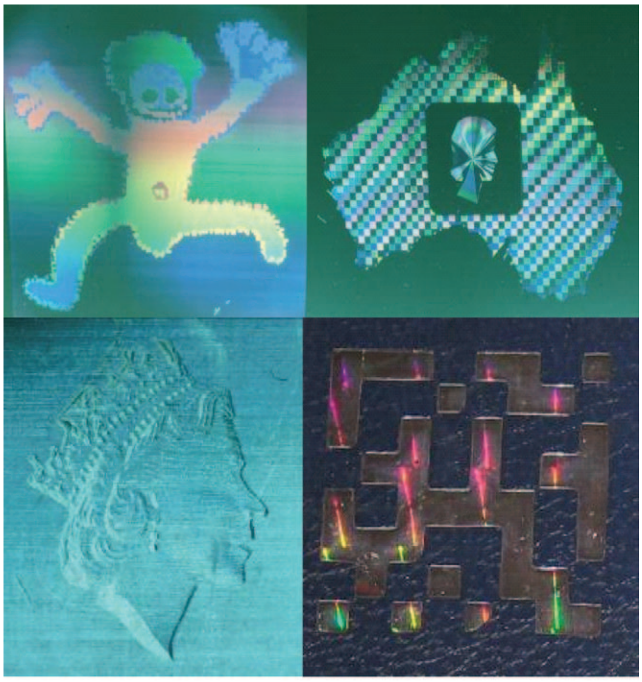

Figure 5. A range of different diffraction grating designs that were made.

Moiré Interference Patterns

Sefton Hamann had discovered that the Moiré interference patterns—developed by modulated line drawings (diffraction gratings) separated by a space—could be predicted. We will concentrate on three of Sefton's designs, a self-authenticating banknote with the letters CIT, and a "walking" dollar sign.

Self-Authenticating Moiré Interference Pattern

This is the simplest way to introduce a Moiré interference pattern into a banknote but it is also the easiest to forge. The two line patterns are placed on opposite ends and sides of the note so that when the note is folded the interference pattern appears. However, each line pattern is accessible to a forger; but they still face the challenge of fine line printing.

CIT Pattern: Reflecting Moiré Interference Pattern

The second option was to use a reflecting foil and only one line pattern; the interference pattern forms from the original lines and the reflected lines. This approach is more difficult to access and forge. One variation of this concept was termed the CIT pattern due to the letters that had been produced on the sample, and was produced with a diazo photographic method and transfer foil technology. These can be seen in the experimental notes (Figure 6).

"Walking" Dollar Sign: Transmission Moiré Interference Pattern

The use of two line patterns, and viewing the image by transmission enabled the production of "walking" dollar signs (Figure 7). As the note is rotated the dollar sign moves from one side to the other. This concept is difficult to incorporate into a note; it was planned to align the second line pattern as part of the incorporation into the note.

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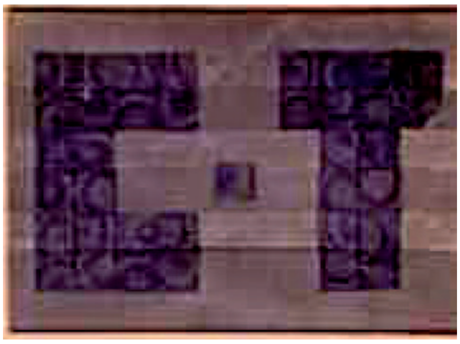

Figure 6. CIT Moiré interference pattern.

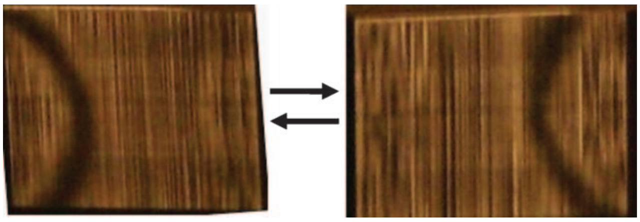

Figure 7. Transmission Moiré interference pattern: a "walking" dollar sign.

The Diffraction Grating Transfer Foil Line

A transfer foil line in effect uses a carrier on which a very thin parcel of films is built up, and which is then transferred to the desired object in either a hot-stamp step or a transfer step (Figure 8). The use of transfer foils enables the time consuming steps involved in building up the multiple layers of the diffraction grating to be done away from the main production line. Initially commercially available foils were evaluated and the original gratings were embossed into the thin metalized layer. However, this approach revealed two major problems:

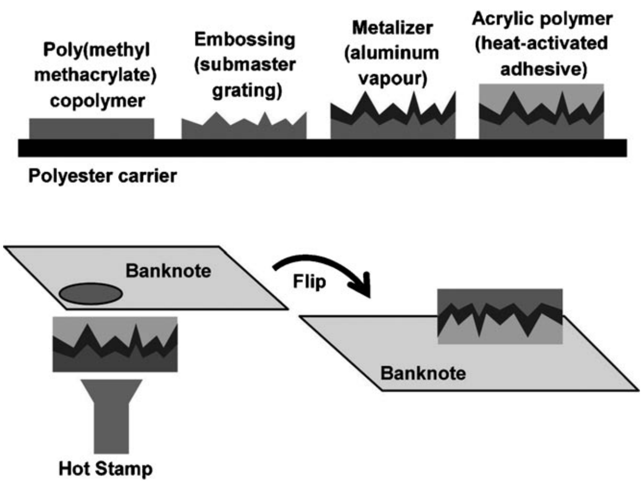

Figure 8. Schematic overview of the hot-stamp transfer foil line for the production of diffraction gratings and their application to the banknote.

1. In order for the foil to release from the carrier, the commercial foils used a release agent, a substance that causes poor adhesion between the carrier and the foil package and therefore assists in the transfer operation. Inevitably some of the release agent is carried with the transferred foil. In most commercial operations this is not a problem, but in this case it was intended to apply an outer coating (to control feel and to protect the diffraction grating) and the presence of release agent would hamper this.
2. When the smooth aluminum layer was embossed technical problems with cracking of the aluminum were experienced and this resulted, among other problems, in poor diffraction efficiency.

The previously identified problems were addressed by carrying out the embossing step before the aluminum was applied. To overcome the poor adhesion resulting from transfer of some release agent the use of such agents was avoided. This was done through careful selection of the polymers used, particularly those in the first layer, by control of the glass transition temperature.

In the initial stages the biaxially oriented polypropylene (BOPP) laminate was coated with polyvinylidene chloride (PVDC) to give a highly reactive surface, which was more receptive to ink and adhesion of the diffraction grating. This coating was used because in the initial set up it was not possible to oxidize the surface with a corona discharge and then immediately follow with printing; and a corona-discharged surface loses its surface properties on ageing. However, PVDC eliminates hydrochloric acid on exposure to sunlight, which can attack the banknote, particularly the aluminum of the diffraction grating. The release of hydrochloric acid could be controlled by the use of dimethylaminoethyl methacrylate (DMAEMA) copolymers in the diffraction grating foil. A more permanent solution was to eventually set up an inline corona discharge, printing, and foil application and avoid the use of PVDC.

The hot stamp or transfer step also offered the opportunity to transfer complex patterns which further complicated any attempt to simulate the grating. CSIRO was to use this foil transfer technology for all of their OVDs. In the 1988 Bicentennial \$10 note the foil package is barely detectable when the fingers are passed over the grating; it is only a few microns thick.

Additional Security in the Diffraction Grating Foil

Apart from the very thin package which constitutes the diffraction grating, careful attention was paid to the composition of the polymers used in the diffraction grating package. In this project one has to consider what the forger might do; a possible method of forging gratings from a banknote would be to use some technique to selectively remove the outer layers and expose the grating. An obvious possibility is to use a solvent to dissolve the outer layers (but not the inner layers) and whilst this would be difficult it was a possibility. Hence polymers that could be lightly cross-linked were used as this makes the polymer layer insoluble. A hydroxy-containing

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polymer was cross-linked with urea formaldehyde. It also means that the grating will swell and distort if a forgery is attempted.

Substrate

The RBA was never keen to move away from traditional banknote paper. One compelling reason for this was that any new substrate had to be capable of mixing with conventional banknotes; it is not possible to replace all banknotes overnight. Automatic teller machines were a major issue of concern as was the use of rapid processing of notes through machines which denominate and authenticate the note.

Early experiments on synthetic papers used either natural (wood, leather) or synthetic (polyvinyl alcohol) fibers. Although each of these gave unique substrates this was not evident to the public, hence failing the "person in the street" test for detection of a forgery. Previously, paper made of polyethylene fibers had been used in banknotes to improve durability. Initially various laminates were made which included the following:

1. A laminate with paper at/in the center on which the banknote design was printed. The outer layers were composed of various polymers, for example, polyethylene, poly(vinyl chloride).
2. A laminate in which the print was on the inside so that it would be protected and secure.
3. As in 2, but incorporating the security devices within the layer.

It was quickly discovered that smooth plastic films were unacceptable because they stuck together. Thereafter in all of the above laminates the surface was controlled by embossing techniques, that is, imprinting a pattern into the heated plastic. In one case an embossing plate was made to replicate the surface of an existing banknote. Later the use of a polyurethane varnish as the outer layer was favored. To achieve a substrate with great versatility and durability reinforced laminates were also studied using a variety of plastics and synthetic woven meshes.

Within CSIRO the various stages in marketing the new banknotes were coded with the number representing the year the CSIRO team expected the note to be on the market. Thus the following points outline the CSIRO marketing strategy:

- 1975—Strand 75: A woven polyester laminate without OVD's but a clear area achieved by punching holes. This was based on a Terylene (polyethylene terephthate)/high density polyethylene laminate.
- 1976—Strand 76: This note was to use the substrate of Strand 75 without punching holes but incorporating OVD's by transfer foil techniques (this could not include Moiré interference patterns but included gold foil, photochromic inks, and counting devices).
- 1977—Strand 77: The Strand 75 laminate with punched holes to receive Moiré interference patterns etc.
- 1978—Strand 78: This was to be based on a new generation of plastic laminates without a woven inner reinforcing mesh.

With the passage of time the aim became a clear plastic laminate with a clear area and a diffraction grating.

Strand 75

Of the various woven fabrics investigated we eventually selected a very fine woven polyethylene terephthate. This layer of Terylene was sandwiched between layers of polyethylene and these layers contained white pigment to make the substrate opaque (Figure 9).

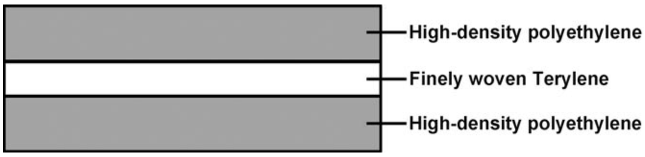

Figure 9. Schematic of layers of Strand 75.

Strand 75 was an extremely durable, virtually tear-proof banknote, and had great appeal. This substrate was used for the early notes and early testing by the RBA, including "blind" tests with bank tellers, and enabled us to progress the project to a stage where the RBA made a major commitment to the project.

$7 Notes

Partly as a joke, but also as a security precaution in case our experimental notes were lost, test notes were printed using denominations not used in the Australian currency system; $7 and $3 notes. In the $7 two circles were present, designated for the OVDs. Initially the idea was to punch these areas out to leave holes into which the pre-prepared OVD would be placed. A film of plastic on either side would hold the OVD in place and protect it (Figure 10).

Figure 10. Experimental $7 note printed on Strand 75 with two circles cut for OVDs.

Whilst this method was workable in the laboratory, on a pilot production line major problems were experienced; firstly it was difficult to cut the reinforcing fabric cleanly, and secondly inserting the device was slow and production efficiency was lost. However, overcoming these limitations

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led to two critical developments which were to be central to the final success of the project. These were:

1. The development of transfer foils (previously described) which allowed for the transfer of OVDs onto Strand 75 without punching holes.
2. The development of Strand 78, a clear plastic film with no reinforcing mesh. This was to be the substrate of the banknote issued in Australia in 1988 and thereafter.

Strand 78

The move to clear plastic film was a major technological challenge and a dramatic change in thinking. However, it offered much more efficient production and added security; the use of a see-through area in a plastic film forces the forger to also use plastic film, making it a simple but very effective security feature.

Choice of Plastic

The technical challenges of matching the mechanical properties of a fiber-based substrate (paper) with a molecular film (plastic) are significant. There are a number of properties needed in banknote paper including abrasion resistance, tear resistance, and flexibility. That no plastic films which met these specifications were commercially available was an advantage because it meant the forger would be unable to easily obtain the substrate. In fact it was soon realized that to satisfy the requirements of flexibility, tear resistance, and handling capability with existing notes we would need a laminate about the same thickness as a conventional banknote, 80 μm.

Laminates of all the common plastics, that is, polyethylene (all densities and combinations including linear low density (LLDPE)), polyvinyl chloride, and BOPP, were prepared by either heat sealing or using adhesives. BOPP was of great interest as it most closely matched rag paper; hence it was given the codename Strand 78. The one property where it did not match rag paper was in folding where it "bounced back". Eventually the RBA were convinced that Strand 78 was different, not inferior, in this property.

A variety of BOPP films made by the tenter and bubble processes were available, usually as coextruded laminates. They also varied in the ratio of the degree of orientation in the machine and transverse directions of the film (Figure 11).

All of these films were evaluated as well as various CSIRO modifications, but eventually a LLDPE/BOPP/LLDPE film was settled on. Two or three of these were heat laminated together to achieve the required 80–90 μm thickness (Figure 12).

Feel of Plastic

"Feel" is a complex interaction of various factors, and there was great resistance to the use of plastic by conservative bankers. Plastic was considered "cheap" and not appropriate for a quality item such as a banknote. However, this was considered by the CSIRO team to be a preconceived prejudice and not a reality, hence this view needed to change.

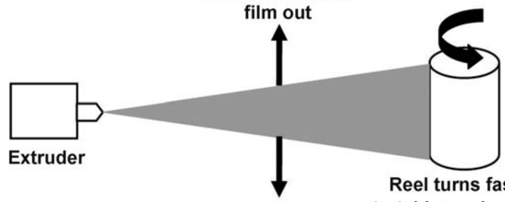

Figure 11. Diagram of biaxially oriented polypropylene (BOPP) prepared using the tenter process. BOPP prepared by the bubble process was also used.

Figure 12. Schematic showing the composition of Strand 78.

Indeed, in a banknote the outer surface which the fingers touch is not the substrate at all but the ink layers. Furthermore for technical reasons, (protection of diffraction gratings, etc.) the whole note was over coated with a clear polymer vanish (a polyurethane). The chemical structure of the polyurethane could be varied to make the coating more or less greasy (hydrophobic). A compromise was needed between a coating with better feel (less greasy) which will pick up more dirt, and a slightly more greasy coating, with a less acceptable feel, but more resistance to dirt.

The physics of the coating also influences the "feel" so fine silica particles were introduced into the polyurethane varnish. Thus the surface texture and the feel could be controlled over a wide range of options by controlling the physics and chemistry of the coating. Eventually "blind" tests were carried out which convinced the RBA that we could achieve acceptable feel for the notes.

Production Challenges

From the first suggestion of using diffraction gratings and to the use of plastic processing production methods, the RBA staff involved in note printing had been attracted to the proposed all-web process. They only needed to be convinced that such a process was viable. At that time (1970s) banknotes produced in most countries used inks that required up to two weeks drying. It was a costly process in both labor and materials. A number of production options were considered and whilst each offered advantages the following option was chosen as it allowed simultaneous development of the OVD features and the plastic laminate (Figure 13).

Building the Pilot Production Line

This project was classified as "secret" so there were restrictions on what could be disclosed to the outside world.

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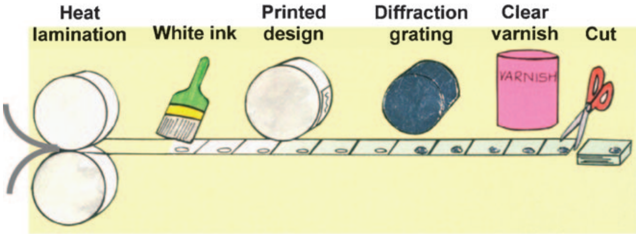

Figure 13. Schematic of the production method chosen, using an all-web process.

The "need to know" approach was used when talking to colleagues in industry and in academia for specific information, for example: what materials would be suitable for the heat rollers. It is to everyone's credit that the secret nature of the project was protected. At CSIRO's laboratories, a 15 cm laminator and transfer foil lines were built, printing equipment set up, test methods devised, and all engineering aspects of the project were tackled. The 15 cm laminator was a world first for heat lamination of Strand 75 and Strand 78.

Testing the New Notes

Testing a revolutionary new banknote poses problems rarely encountered elsewhere. It is not possible to trial a new banknote in the field, so the challenge is how to use laboratory tests as a guide to performance. Great confidence is needed in the tests since the release of a new banknote is an extremely serious undertaking. If a mistake is made, the note becomes a collector's item and the nation's economy is in crisis.

In conventional tests the new plastic notes were vastly superior to paper banknotes. For example in the abrasion test the disk is in contact with the varnish on the plastic note whereas in paper notes it contacts directly onto the ink.

In the case of a revolutionary banknote there was always a worry about some obscure situation that had not been tested for. As a result literally hundreds of tests were carried out, many obvious, some not. Hence the notes were tested for the effect of all possible foods, liquors, detergents, nail lacquers, and beauty treatments. Air travel and deep sea diving were simulated. Many of the staff carried notes in their wallets, and used them to "buy" morning tea in the security of our production building. The RBA staff also constantly came up with "what if" questions: "What if the note is subjected to…" and some bizarre set of conditions. One test that had not initially been considered was requested by the Federal Police; can you collect fingerprints from the new notes? Luckily, all the existing methods were still able to be used.

Tests, suitably modified from other areas, were used to extend confidence in the notes. The "scrunch" test (from the leather industry) was an example: here the pistons at each corner of the note were programmed to push and pull the note (Figure 14).

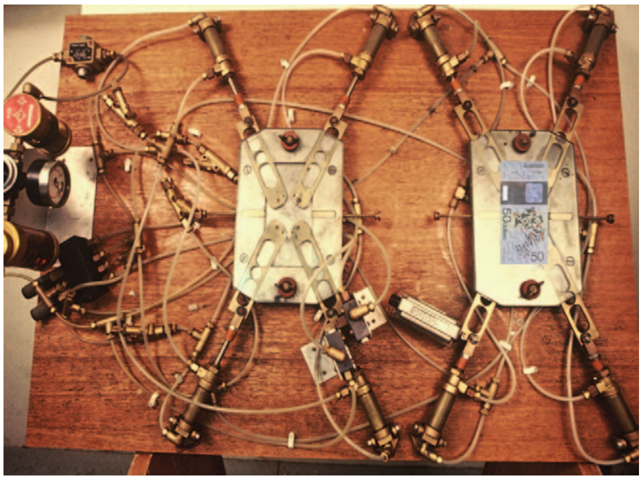

Figure 14. Scrunch test, adapted from the leather industry.

The Turbula or Tumbler Test

Of particular significance was the so-called Turbula, or Tumble Test that was developed in-house. This test was to be critical in providing data for both the release of the notes to the public and the prediction of their lifetime (necessary to assess the economic viability of new notes). In fact, in the evaluation of the technology by an American expert, the total test regime developed was of significant value because the CSIRO team had correlated laboratory testing with field performance.

The devised test used weights placed in the corners of the note which was then tumbled in a kerosene tin with controlled amounts of synthetic dirt, an abrasive, and even artificial sweat. The test was calibrated by first using mint-condition paper notes. The time needed in the Turbula test to reach a given level of dirt pick-up or tear was compared to the lifetime of paper notes withdrawn from circulation by the bank tellers. Then the plastic notes could be tested and an estimate of their expected lifetime was made. This test was crucial in deciding to release the note and proved remarkably accurate, maybe slightly conservative, data in predicting the field performance of the notes (Figure 15).

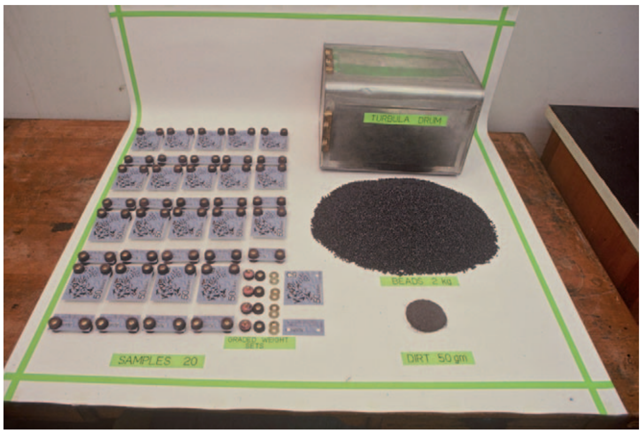

Figure 15. The Turbula test with note samples, an abrasive, and synthetic dirt.

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Tear Initiation and Tear Propagation: Embossing versus Overprint Varnish

During this extensive test regime puzzling results were obtained on the tearing of Strand 78. It is extremely difficult to initiate a tear in BOPP but once started the tear propagates rapidly. We traced this to the embossing step, therefore in future only the polyurethane varnish was used which had added advantages in protection of all ink/OVDs.

Economics

After development of a process for producing a durable substrate, and therefore a more secure banknote, the question of the economics of the experimental note needed to be addressed. The question of the price of security is not easily answered even in paper note technology and, given a range of OVDs, the lifetime of an experimental note would be determined by the least durable OVD. The question of what price the RBA would pay for a more secure currency was never answered. Indeed, in the Bicentennial note the question was avoided by having better overall durability than the paper notes, more than enough to offset the increased cost.

An economic analysis indicated that the experimental notes would cost about 1.3 times that of paper notes but the predicted lifetime was at least 3–4 times longer, so overall our product was viable. Field experience more than supported this prediction. At present Securency International Pty Ltd claim plastic notes last up to 4 times longer than paper notes and over 10 years the total cost of plastic note production is half that of paper notes.

Technology Transfer—A Challenging Time

The reader needs to appreciate that the two organizations, CSIRO and RBA, were dramatically different. Whilst both were Australian Government bodies the RBA Note Printing Department was set up as an importer of technology. It had little or no experience in research and development and was not staffed to do this. Consequently the revolutionary, as distinct from evolutionary, approach CSIRO were proposing was treated with great concern by some senior RBA staff.

It was quickly realized during meetings that samples which looked like banknotes were appreciated much more than mere abstract demonstrations of scientific principles. As a consequence sheets of our Strand 75 or Strand 78 would be supplied to the Note Printing Branch of the RBA who in turn printed conventional (existing) note designs on these. This also allowed CSIRO to constantly draw attention to the quality of the intaglio print on Strand 78. On a smooth plastic film the intaglio stands higher, as would be expected because the inks do not "wick" down the fibers as they do with paper.

During this period the Note Printing Branch of the RBA was building a state of the art new printing works in Melbourne, and they had invested heavily in the latest equipment. The idea grew that if this equipment was used to print the new notes they could get to market more quickly and the large capital investment would not be lost.

A Compromise Production Line

As a result of the return to the use of intaglio printing the new production process was altered so that the laminate, after opacification of the clear plastic, was cut into sheets. Some of the production efficiency was lost but on the positive side the traditional printers were now much happier. The production line for plastic notes was similar to that used for paper notes except now we made our own "paper" (Strand 78) and then after conventional printing we added the security devices. This process was accepted as an interim step to the all-web process but in fact has become the standard.

Release of Banknotes

1988 First Release

After the Governor of the RBA, Mr. R. A. Johnston AC, had made the enormous decision to release these novel banknotes he was faced with the question of what denomination note to issue first and how many. He and his team decided to do the next best thing to a "field trial" and issue a limited number of special occasion notes; the approaching Australian Bicentennial year 1988 was chosen for this and the issued $10 note is shown below (Figure 16).

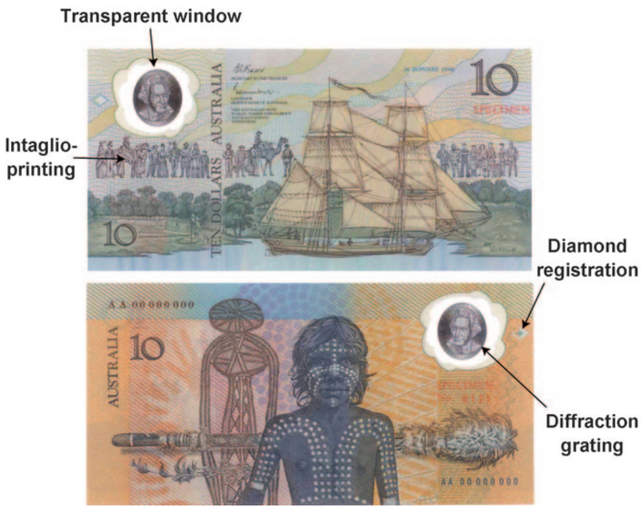

Figure 16. The Australian Bicentennial $10 note released in 1988.

After the release, market analysis reported the following response from the population:

1. Overall acceptance was high (48%) and outright dislike was only 26%.
2. The main perceived advantages were increased durability and cleanliness.
3. The main difference was the property of bounce-back—the plastic notes fold differently to paper.

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David Solomon was honored to be invited by Governor Johnston to the press release of the Bicentennial $10 note in 1987. It was a sobering experience as a scientist. The Governor described the note, as did the press release, as being printed on a synthetic polymer substrate. This was part of the agreed description owing to the perception that plastic is "cheap and nasty" and therefore not appropriate for a quality article such as a banknote. Early in the press conference a reporter asked David whether synthetic polymer substrate was "just a fancy name for plastic?" The answer was yes. The press was far more interested in the design of the note and paid little attention to the improved security. Overwhelmingly the questions were to the artist and the design! The problem of communicating scientific achievements is not trivial; design is easy for the public and the press to appreciate.

Release of Other Notes

From 1992 to 1996 the Note Issue Department replaced all Australian notes with plastic. In 1990 the Note Printing Branch of the RBA was renamed Note Printing Australia and was established as a separately incorporated wholly owned subsidiary of RBA in 1998. They have extended their horizons to include passports. Securency Pty Ltd, which supplies the polymer substrate (plastic), was formed in 1996 as a joint venture between the RBA and Innovia films. They have expanded from banknotes to other security documents; passports, land titles, and documents of identity.

The export records of Securency and Note Printing Australia are impressive; over 27 countries are using the technology and another processing plant has also been set up in Mexico.

Does the Technology Work?

The answer is an emphatic yes. Romania introduced plastic banknotes and reduced counterfeits by 98%, New Zealand and Brazil had similar dramatic effects. Perhaps the most obvious confidence in the security of plastic notes is the issue by Brunei of a limited number of $10,000 banknotes in 2006.

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